Mokyr (1990)

CHAPTER FOUR

The Renaissance and Beyond: Technology 1500–1750

As noted, by 1500 Europe was no longer the technological backwater it had been in 900, nor was it the upstart imitator of 1200. It is clear that Europe owed China a great deal, as Needham has argued tirelessly.[1] Yet in the two centuries before 1500, Europe's technological creativity had become increasingly original. In the later Middle Ages Chinese technology had become, in Landes's phrase, a "magnificent dead end." After 1500 China ceases to be of much interest to the historian of technology. Its use of iron and waterpower did not lead to a Chinese Manchester any more than its knowledge of printing led to a massive outpouring of printed books in China; Su Sung's famous water clock did not cause a large clock to be erected in the center of every town in China. In Chapter 9, I shall examine the Chinese experience in some detail.[2]

In the centuries after 1500, the gap between Europe and the rest of the world gradually widened, even though the age witnessed relatively few macroinventions. Technological progress in the conventional sense continued unabated. The increase in productivity, however, became more gradual and consisted largely of sequences of microinventions and modifications to existing techniques. One ex-

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[1] Much of Needham's persistent defense of the Chinese origins of Western technology is a needed antidote to the Eurocentric histories of technology that are now falling out of style. But Needham may have exaggerated the Chinese influence. It may well be true, as his widely quoted phrase notes, that "the world owes far more to the relatively silent craftsmen of ancient and medieval China than to the Alexandrian mechanics" (Needham, 1969, p. 58). But by 1500 Europe already owed far more to its own silent craftsmen and engineers.

[2] Europe's debts to the Orient were not confined to China. India, Tibet, and even Malaya contributed to European power technology, metallurgy, and textiles (Lynn White, 1978, pp. 43–58).

planation for the absence of discontinuous breakthroughs between 1500 and 1750 is that although there was no scarcity of bold and novel technical ideas, the constraints of workmanship and materials to turn them into reality became binding. If inventions were dated according to the first time they occurred to anyone, rather than the first time they were actually constructed, this period may indeed be regarded just as creative as the Industrial Revolution. But the paddle-wheel boats, calculating machines, parachutes, fountain pens, steam-operated wheels, power looms, and ball bearings envisaged in this age—interesting as they are to the historian of ideas—had no economic impact because they could not be made practical. The paradigmatic inventor of this period was the Dutch-born engineer Cornelis Drebbel (1573–1633), who made minor contributions in a host of areas, including chemical dyes, clockmaking, and furnacemaking, but whose main claim to fame rests on the demonstration of the idea of the submarine in 1624, two-and-a-half centuries before submarines became practicable.

From a purely economic point of view, the most important technological change in terms of its potential contribution to material welfare can hardly be termed an invention at all. The "new husbandry," as it is now called, was a set of modifications in agricultural practice that made its first appearance in the Low Countries by the closing of the Middle Ages. These changes spread, ever so slowly, to England and eastward, but by 1750 their adoption was far from complete and in some areas, including most of France, had hardly begun. Yet the principles of the new husbandry were revolutionary, and their adoption led eventually to increases in agricultural output. The three elements of the new husbandry were all closely related: new crops, stall feeding of cattle, and the elimination of fallowing. The result was that farmers were able to maintain more and better-fed cattle, thus increasing the supply of animal products. Better-fed animals produced more fertilizer, which helped to increase cereal yields. The new fodder crops, such as alfalfa, clover, artificial grasses, turnips, and mangel-wurzels, also turned out to be useful as alternating crops to cereals in new rotations. Some of these crops were nitrogen fixers and all of them broke disease and pest cycles. With the increased supplies of fertilizer and the need to hoe some of the new crops, such as turnips, fallowing the land became less necessary and the practice began gradually to disappear in some regions, increasing the effective supply of arable land. The new husbandry was a tale of complementarities, of mutually reinforcing and symbiotic changes, but it was slow to unfold. Some of the new crops were not suitable to heavy clay soils, others needed better drainage than was available. Capital scarcities, the scattering of plots, and hostility to novel practices by those who were frightened or threatened by them, slowed diffusion. Some scholars believe that the adoption of the new husbandry depended on the enclosure of open fields, but this is now disputed. In any event, the often-used term "agricultural revolution" to denote the introduction of the new husbandry is misleading. There was nothing abrupt about it.

The effect of the new husbandry on living standards is hard to quantify. In many areas its full-scale adoption took place only in the nineteenth century. Even in areas where it was adopted, it is difficult to know exactly how much of the increased food production was attributable to this new technology. Yet most experts agree that in the long term it had profound consequences for the economic well-being of most Europeans. Nevertheless, although it permitted larger quantities of food to be produced, technological progress in farming did little to reduce the toil of the men and women working in the fields. Even the new implements introduced at this time were, by and large, capital- and land saving rather than labor saving. The seed drill is a case in point. In traditional European agriculture, sowing was carried out by *broadcasting,* spreading the seeds by hand. This technique not only wasted seed and led to an uneven utilization of the soil, it also made weeding difficult because of the uneven germination of the plants. In the sixteenth century the practice of "setting" seeds (by using sticks to make holes in which seeds were dropped) was known. The modern seed drill, which deposited seeds into equally spaced holes, greatly increasing the yield-seed ratio, is traditionally associated with Jethro Tull, who built and demonstrated the first prototypes around 1700, though the implement was little used before the nineteenth century. Tull also suggested the introduction of horse hoeing in 1714. New iron plows, introduced first in the Low Countries and then in England, also probably saved more capital than labor. The new plows reduced the friction with the soil by curving the shape of the mouldboard that cut the furrows, and were thus easier to manipulate and handle. It was difficult, however, to shape wood into exactly the desired form, and so after 1650 mouldboards were increasingly made of iron. This led to the disappearance of wheels and the reduction of the number of draft animals required for plowing. In 1730 the Rotherham, or Dutch, plow was patented in England.

In the area of energy use, medieval techniques were improved but not revolutionized. The windmill continued on its tortuous road to ever greater efficiency when Dutch and Italian engineers in the sixteenth century introduced the tower mill, which left the structure permanent and made the axis and roof pivot toward an optimal angle. By the seventeenth century the windmill supplied the Dutch economy, at that time the economic *wunderkind* of Europe, with a cheap, clean, and inexhaustible source of energy that is the envy of today's ecologists. The Dutch were often able to increase the efficiency of manufacturing using wind power through technical ingenuity, as was the case with the *Hollander,* a device invented around 1670 that was used in papermaking. It consisted of horizontal rollers with spikes and mallets that ripped up the rags used for pulping (Hunter, 1930, pp. 170–71). Thanks to the *Hollander,* Dutch paper was of a higher quality than paper made elsewhere in Europe. Windpower was also adapted to drive the sawmills in the Zaan area, where for many decades the Dutch shipyards produced the best ships of Europe. Waterpower generation and transmission, too, became more sophisticated. Yet, in spite of the attractive features of wind-

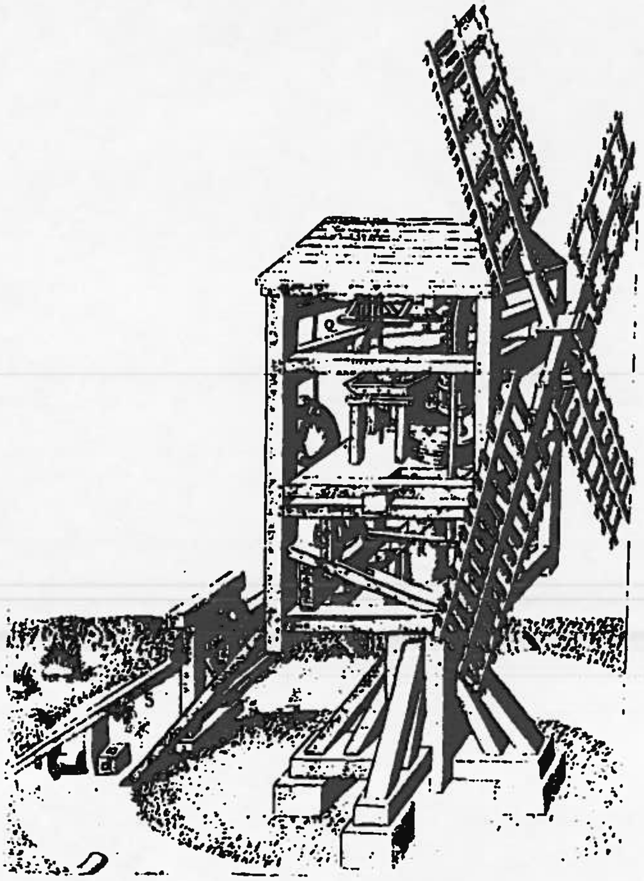

Figure 15. Corn-grinding windmill. This type of mill is known as a *post-mill,* as the entire structure swivels.

Source: The Various and Ingenious Machines of Agostino Ramelli, translated by Martha Teach Gnudi, Dover Publications, Inc.

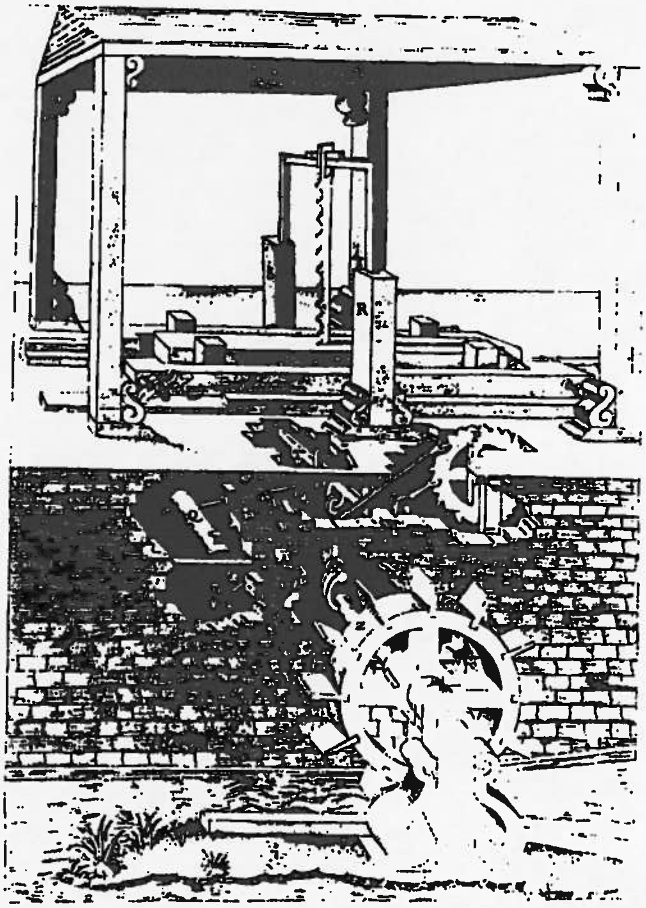

Figure 16. Water-driven sawmill as depicted by Ramelli in 1588.
Source: The Various and Ingenious Machines of Agostino Ramelli, translated by Martha Teach Gnudi, Dover Publications, Inc.

and waterpower, there was a perceptible need for a machine that would not depend on the vicissitudes of European weather.

On or immediately below the surface of Europe lay vast supplies of stored-up solar energy in the form of peat and coal. The use of peat and coal in Europe was not new in 1500, but its geographic expansion and the increase in the number of its uses have prompted some to consider it as important as the greatest inventions of the Industrial Revolution.[3] In Britain and in a few places on the Conti-

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[3] Consider John U. Nef's statement (1964, p. 170): "by the mid-seventeenth century a new industrial structure was being built in England on coal, and this structure provided the basis for the industrialized Great Britain of the nineteenth century."

nent, including the Principality of Liège in what is today eastern Belgium, coal was used in iron forges, glassmaking, saltmaking, soap boiling, alum production, and lime burning.[4] The fuel-intensive brewing industry could not use regular coal, because it ruined the taste of the beer, but British brewers learned to use charred coal, later known as coke. Similarly, the Dutch used their abundant peat supplies extensively for home heating, as well as for a myriad of industries that helped create the Dutch Golden Age. Brickmakers, madder producers, kiln operators, salt refiners, bakeries, bleachers, tilemakers, and many others made extensive use of peat. Only two major uses of fossil fuels remained elusive: the smelting of iron and the efficient conversion of thermal energy (heat) into kinetic energy (work).

The two centuries after 1500 witnessed major improvements in the use of blast furnaces. Their size and efficiency increased substantially: in 1500 a best-practice blast furnace could produce 1200 kg/day, by 1700 an average figure was more than 2,000 kg/day, and fuel consumption fell in the process. An important improvement was the adoption of a continuous smelting process, in which ore and fuel were fed into the furnace continuously, producing a continuous flow of pig iron. Such a "found day" could last up to 40 weeks by 1700. This period also saw the use of reverberatory furnaces, first described by the Italian Vanoccio Biringuccio in his *De la Pirotechnia* (1540) and applied to the English glass industry around 1610. These furnaces eliminated the chimney and used underground pipes to draw in fresh air. A dome-shaped roof lined with refractory clay reflected the heat back into the oven, generating very high temperatures. Another improvement was the *trompe,* dating from the mid-sixteenth century, which used flowing water to blow air into the forge like a reversed air-lift pump. Yet there is some evidence (Smith and Forbes, 1957, p. 30) that these technical improvements were insufficient to prevent rising fuel and labor costs from raising the price of iron. In the refining and shaping sectors of the iron industry, the most important innovation was the introduction of rotary action, usually waterpowered. Rolling mills, which produced flat sheets of wrought iron, and slitting mills, which cut them into narrow strips for the manufacture of nails, wire, pins, cutlery, and other final products were operating in the Liège region around 1600, where they were a significant factor in the growth of the industry (Gutmann, 1988, p. 62). In England rolling was applied to lead frames

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[4] Alum is a double sulfate of ammonium and a trivalent metal. It is used widely in a range of chemical industries, including dyeing, tanning, paper making, and pharmaceuticals.

Figure 17. Iron-smelting furnace and forge, mid-sixteenth century.
Source: Georgius Agricola, *De re metallica*, 1556.

used for windows in 1568, and in the iron industry in the middle of the seventeenth century, although the final products were of a low quality (Tylecote, 1976, p. 90).

Economic activity expanded not only sideways but also downward, into the earth itself. From about 1450, mining, especially in central Europe, entered an age of progress unlike anything ever seen before (Molenda, 1988). Here, too, we have no famous inventors, just an endless succession of anonymous improvements on the margin. We do have, however, a hero of sorts, namely Georg Bauer, who, under his latinized name of Georgius Agricola, wrote *De Re Metallica*, published posthumously in 1556. *De Re Metallica* is one of the finest and most detailed books on mining engineering ever written.[5] From it we can infer the improvements introduced into mining after 1450. Agricola describes the machines used for drainage and ventilation, the cranes used for hauling the ore, the construction of shafts, even the sampling of ore quality. The technical problems in mining appear to be universal: flooding, explosions, and vertical haulage lead the list. Germans led Europe and the world in mining technology, developing the transmission of waterpower to high-elevation mines from waterwheels in the valleys by means of overland rod systems; applying gunpowder for blasting rocks; pioneering the use of rails for underground transport; using horse-operated treadmills to run windlasses; and above all developing a variety of pumping devices (that were subsequently applied to fire fighting and other uses).[6] Of comparable influence was the Bohemian mining engineer, Lazarus Ercker, whose magnum opus on mineral ores and mining techniques, published in 1574, was used for generations as a manual on assaying and sampling. Agricola and Ercker were both empiricists, not scientists. There was no theory in their work, just descriptions of things that worked: mining engineering remained almost entirely an empirical body of knowledge. Neither Agricola nor Ercker paid much attention to iron, by far the most important industrial material of the time. Nor were their insights uniformly valuable. Ercker ([1580] 1951, p. 223) explains, for example, that he has reluctantly been forced into the conclusion that iron turns into copper after being treated with vitriol (sulfuric acid). Cyril Stanley Smith, his editor, remarks that this error is a good example of how difficult it is to understand chemical processes without good quantitative measurements. Still, the contribution of scientists, if not science, to mining technology was substantial. The greatest minds of the seventeenth century, from Galileo to Newton, were concerned with the problems of air circulation, safety, pumping, mineralogy and assaying, and the raising of coal and ore from the mines (Merton, 1938, pp. 147–59).

The large number of technical "how-to" books published after 1450 provided a vehicle through which technology was diffused through Europe. Renaissance engineers wrote about a variety of machines and contraptions, many of them serving architectural and military

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[5] Agricola's work was all but forgotten until his work was rediscovered by a young American mining engineer named Herbert Hoover who, with his wife, translated the work from Latin and published it in 1912, before moving on to other matters.

[6] It is with only a little exaggeration that one historian refers to this period as "the age of the pump" (Burstall, 1965, p. 144). Some of the writers on technical matters of the time devoted much attention to describing a variety of pumps. In addition to Agricola, there was Agostino Ramelli, whose massive book *Dell' Artificiose Machine* ([1588] 1976), contained descriptions of over 100 pumps.

Figure 18. Furnace for the melting of copper and lead as depicted by Lazarus Ercker in 1580.
Source: Lazarus Ercker, *Treatise on ores and assaying*, 1580.

purposes. Thus, a technical literature emerged, written by engineers for engineers, and technical knowledge became increasingly communicable and thus cumulative. One of the earliest and greatest of the technical writers was the Sienese engineer Marianus Jacobus Taccola, whose *De Machinis Libri* summarized the state of the art in machine technology in the middle of the fifteenth century. His influence was such that he has been called "the Sienese Archimedes." Jacques Besson's *Theatrum Instrumentarum et Machinarum*, published in Latin and French in 1569, went through three translations and seven editions in the following 35 years. The German Hieronymus Brunschwygk published a book on distilleries, *Liber de Arte Distillandi* (1500), which went through numerous editions and translations. This literature illustrates the growing respect shown by Europeans for machines and the people who made them. Yet outside a few areas, it is unclear that these writings had much effect on the industrial practices of the time (Gille, 1966). Cipolla (1972) has pointed out that Vittorio Zonca's *Nuovo Teatro di Machine et Edificii,* first published in 1607, contained a detailed description of the supposedly secret silk throwing machine in use in northern Italy, and that this book was available in Britain from 1620. Yet silk throwing did not come to Britain until a century later, after John Lombe, one of the greatest industrial spies of history, spent two years in Italy studying the intricacies of the technology.

The meticulous description in books on engineering and mining may leave a misleading impression that the machines described by Agricola, Ramelli, and others were standard equipment in Renaissance Europe. In fact, the gap between the best-practice technique and the average-practice technique was large. For one thing, many of the complex machines described were simply too expensive; even if they would eventually pay for themselves, it was often difficult for a machine builder or engineer to cover the costs of construction or to borrow the necessary funds. In other cases, lack of local skilled labor and mechanics made it difficult to adapt a machine that worked well on one site to operate on another under different circumstances. Innovation remained a live force, but its effects on productivity came only slowly. It may well be that most of the increases in labor productivity in engineering industries and mining were the result of better tools, economies of scale, and a more efficient organization of labor.

Among the successes of Renaissance technology were its achievements in hydraulic engineering, an area in which the classical world had excelled, but which had been neglected for many centuries. Italian engineers, including Leonardo Da Vinci, wrote extensively about dams, pumps, conduits, and tunnels. The leading practical hydraulic engineers of the time were Dutch. After the disastrous floods of 1421, Dutch engineers gradually reclaimed their land, protecting it from the large rivers and the sea, employing power-driven scoop wheels and screw pumps. They used the experience they accumulated to help solve similar problems in the marshes of Poitou and to drain the English Fens in the seventeenth century. From Venice to Lübeck, hydraulic engineers struggled with oceans, rivers, and swamps. Advances in hydraulic engineering helped Europeans make progress in one of the areas in which they were still much behind the Romans, the supply of fresh water. Mechanical-powered water supply systems were installed in Toledo (1526), Augsburg (1548), and London (1582). One of the most famous engineering feats of the baroque era was the Marly pumping plant, built by the Walloon engineer Arnold de Ville between 1678 and 1685, to provide water to

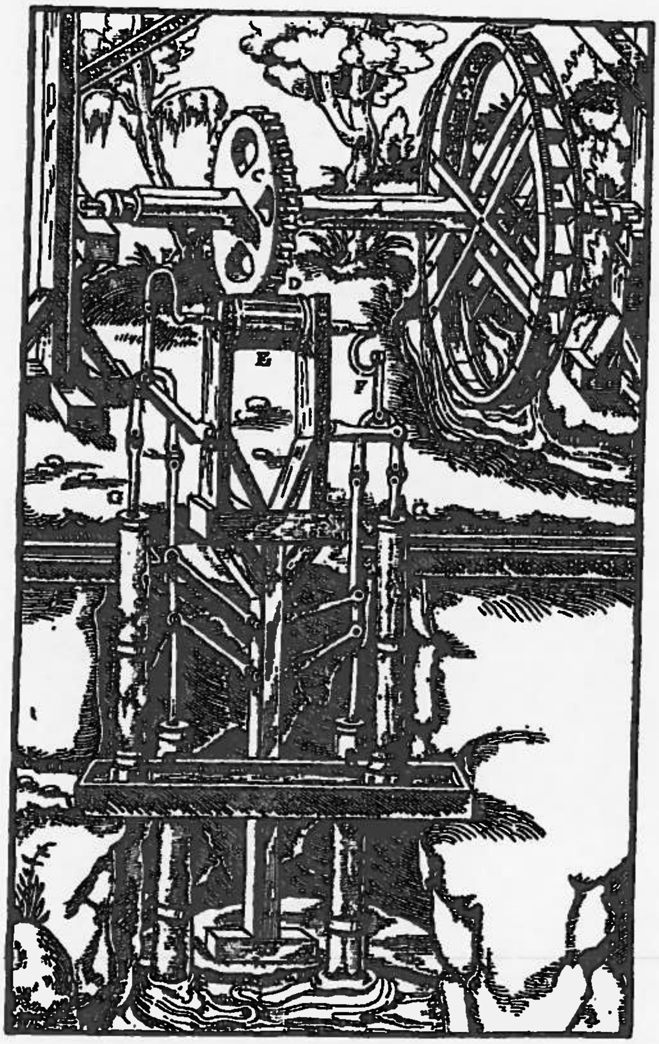

Figure 19. Sixteenth-century water-powered mining pump as depicted by Agricola.
Source: Georgius Argicola, *De re metallica*, 1556.

the royal palaces at Versailles, Marly, and Trianon. Fourteen huge waterwheels drove 221 pumps, and while the project had flaws (the pumps were inefficient and noisy), it nevertheless stands out as a triumph of seventeenth-century hydraulic engineering. In terms of sheer size, the largest hydraulic project was the Languedoc Canal, completed in 1681, which connected the Atlantic Ocean with the Mediterranean, using 26 locks for the rising portion from Toulouse to the summit and another 74 downhill to Sète.

In textiles, the spinning wheel was provided with a treadle and a crank that increased its ease of operation. The foot-operated drive freed both hands of the operator to tend the yarn. The stocking frame, a hand-operated knitting machine consisting of hooks built on a wooden frame, invented by William Lee, a Nottinghamshire clergyman in 1589. The frame diffused throughout Europe in the first half of the seventeenth century, and counts as one of the few true macroinventions of this age. The Dutch loom, which could weave up to twenty-four ribbons simultaneously, dates from 1604, its invention attributed to the Dutchman Willem Dircxz van Sonnevelt. New fabrics were also introduced around this time and it is in this period that Europeans first started to make cotton products themselves, rather than importing them from the Orient. With the predominance of cotton in Western Europe still far in the future, the early modern period saw a great expansion of the production of worsteds, a woolen product made of coarse wool that had been combed rather than carded. Worsted did not need fulling, which made it relatively cheap, and it was lighter than regular wool, making it more attractive to consumers in warmer climates. Although no great technological breakthroughs were made, the techniques spread from the Continent to Britain, where it became a major part of the industrial sector known as the "new draperies." From a mechanical point of view, the most interesting innovation was the development of the silk-throwing mill. By the seventeenth century, large silk mills had been erected in the Piedmont and Tuscany regions of Italy that could be called factories in every respect. The Bologna-type mills set up by the Lombe half-brothers in Derby in 1717 consisted of a huge waterwheel driving no fewer than 25,000 small wheels that simultaneously threw and reeled silk on a vast scale.

The geographic discoveries were in many ways the dominant feature of this age. In some ways, the discoveries may have slowed the rate of technological progress, absorbing much of the energies of the more adventurous and resourceful Europeans. Yet technological and geographical discovery were often complementary, and the interplay between Smithian growth and Schumpeterian growth took many forms. One of these was the design of ships. Although few Renaissance innovations in shipbuilding and seafaring techniques were as dramatic as those of the later Middle Ages, progress was made in less spectacular but economically crucial areas, leading to significant reductions in the cost of transport. Dutch shipbuilding yards were at the center of progress. In 1570, a Dutch sailor came up with the idea of a separate topmast, fitted in a cap on top of the mainmast. The advantage was twofold: the tall and expensive spar trees used to make mainmasts could be dispensed with, and the topmast could be removed in bad weather, reducing the chance of damage to the mainmast (Unger, 1978, p. 28). The Dutch shipbuilding industry led the movement toward specialization, building at least 39 different types of canal- and riverboats alone. The culmination of this trend was the Dutch *fluytschip*, or "flute," according to tradition first built in 1595. The *fluytschip* was the crowning achievement of a century of continuous rationalization and improvement. It was cheap to build and operate, carried a small crew and large cargoes, and until imitation caught up with them, enabled the Dutch to undercut the French and British carrying trade by 30–50 percent (Derry and Williams, 1960, pp. 209–10). With the introduction of heavy naval guns, ships in northern Europe became specialized again, as they had been in Roman times and in the Mediterranean in the Middle Ages. Cargo ships and naval vessels were differentiated, and large unarmed merchant ships sailed in convoys, protected by heavily armed men-of-war (Unger, 1981). In navigation, too, improvement was marginal, with better quadrants and maps, but the greatest difficulty seamen faced—determining accurate longitude while at sea—was not satisfactorily solved until the eighteenth century.[7]

Transportation over the land remained slow and awkward, but gradually became less so during the Renaissance. Better carriages, using leather straps as primitive springs, appear during this period, reputedly first in the Hungarian town of Kocsi, or Kocs, hence the English term "coach." By the late seventeenth century stagecoaches had steel springs, glass windows, and brakes. Renaissance Europe also experienced a revival of an international postal system. As Europe became more integrated and unified, technology could spread faster as people and ideas moved about more easily.

Discoveries in the New World and elsewhere had a clear and visible impact on Europe. Crops from other continents were introduced into Europe, or were cultivated abroad by European entrepreneurs for the sake of European consumers. Maize (corn), tobacco, and potatoes were brought to Europe from the New World. Tobacco was grown successfully in many places in Europe, though the quality rarely matched that of the best varieties grown in America. Maize was introduced in southern France and Italy as a lower-class food. The potato eventually had the greatest impact on European diets as a nutritious and cheap food, first in Ireland, then in the Low Countries, and after 1800 throughout most of Europe. Similarly, Europeans were exposed to new industrial goods that led to the growth

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[7] The problem was essentially one of building an accurate clock that would withstand motion on sailing ships, so that one could compare the time on board as measured from solar charts with the time at a fixed point, such as Greenwich; a comparison between the two allows the inference of longitude. The best scientific minds of the seventeenth century became involved in the problem, but the technical difficulties proved stubborn. In 1714 a specially established Board of Longitude promised the huge sum of £20,000 to "such person as shall discern the longitude at sea." A clock accurate enough to solve the problem was built by John Harrison in 1762.

of import substitutes. One of these was the chinaware industry, begun in Saxony in 1712. Another was the British cotton industry, which emerged in response to a desire to compete with the high-quality Indian cotton goods known as calicoes.

The age of discoveries was thus the age of exposure effects, in which technological change primarily took the form of observing alien technologies and crops and transplanting them elsewhere. The aggressive Europeans adopted crops from America in exchange for the livestock, wheat, and grapes they transplanted into the New World. Furthermore, they also transplanted non-European flora from America into Africa and Asia and back in a massive act of what could be called ecological arbitrage.[8] Thus, they introduced bananas, sugar, and rice into the New World, and cassava (also known as manioc) into Africa, where it eventually became the staple crop in many areas (Crosby, 1972, p. 187). Sweet potatoes and peanuts were a great success in China after Portuguese traders brought them there from America in the sixteenth century.

The discoveries, together with improved technology, also increased the supply of fish, an important part of the European diet. Because domesticated animals were expensive to raise and the supply of game was small in most parts of Europe, fish was indispensable as a source of protein. The problem was one of preservation. In medieval times, fresh fish could reach only those living close to sources of supply. Herring was the main catch in Europe, first in the Baltic and later in the North Sea. In the late fourteenth century, Dutch fishermen discovered the technique of gutting and salting fresh herring, which allowed preservation for long periods. By about 1415, they had introduced drift nets, which were towed alongside ships and increased catches substantially. The ships that carried these nets, introduced at about the same time, resembled little floating factories. They carried coopers and salters aboard who processed the fish immediately. These fishing ships, known as *busses*, helped the Dutch establish a domination in North Sea fishing that lasted for centuries. The other major crop provided by the sea was gutted and dried cod, known as stockfish and sold throughout Renaissance Europe. The discovery of huge supplies of codfish off the banks of Newfoundland in 1497 by John Cabot, and the use of a new type of line with thousands of hooks, gave the Europeans a new and unexpected free lunch of dried cod, not appetizing perhaps by modern standards, but rich in protein.

Above all, the age of discoveries was one of instruments. Instru-

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[8] The ecological consequences of the age of discoveries are explored masterfully by Crosby (1972, 1986).

ments in Western technology came before machines. The affinity of Europeans for gadgets derived to a large extent from the clockmaking industry. Clockmakers revealed the wonders that precision-built spring-driven gears and cogs could achieve. By the middle of the fifteenth century the German town of Nuremberg had become the world's center for gadgets. Its fame is immortalized by E. T. A. Hoffmann and Jacques Offenbach in the tale of the Doll of Nuremberg. Not all instruments were toys, however. Astronomical instruments and compasses were crucial to the worldwide navigation in which Europeans became involved.[9] Military technology required precision for the calibration and sighting of guns. Commerce required precision scales, real estate required odometers. A special branch of the instrument making industry was optics. The earliest spectacle lenses were convex and could aid only the far-sighted. A little before 1500, concave lenses were developed that corrected shortsightedness as well. The telescope was invented by Dutch opticians in the early 1600s. Though of limited direct economic use, the telescope nicely illustrates the pragmatic bent of the European mentality at the time. Within a few years, Prince Maurice of Nassau used the telescope to gaze at the Spanish armies and his sea captains used it to look for cliffs and hostile galleons at sea, while in Padua a mathematician by the name of Galileo used it to gaze at the moons of Jupiter. Technical ideas and gadgets that worked, and worked well regardless of the environment, spread more rapidly than ever before.

The precision instrument industry produced important spillover effects in the manufacturing sector. The main breakthroughs had to await the Industrial Revolution, but the lathe, one of the oldest carpenter's tools in use, underwent improvements as clock- and instrument makers needed precision parts and accurately cut screws, and opticians needed precision-ground lenses. In the sixteenth century the fly wheel and the crank, those irrepressible medieval ideas eternally in search of applications, were applied to the lathe. The greatest lathemaker of the age was Jacques Besson, a French engineer employed by the court of King Charles IX, who built, around 1569, an ingenious and sophisticated screw-cutting machine. The Besson

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[9] From Nuremberg and Augsburg the art of instrumentmaking spread to Louvain in the southern Netherlands and from there to London. The London instrumentmaker Humfray Cole was apprenticed to the Liège craftsman Thomas Gemini. Among Cole's customers were Francis Drake and Martin Frobisher. Gemini himself had studied in the south of Germany. Another German instrumentmaker, Nicholas Kratzer, lived in England for many years. It is interesting to note that although the Germans themselves were little involved in discoveries, the instruments they made were. The European world by 1500 had become sufficiently integrated that knowledge and technique could spread across boundaries without difficulty.

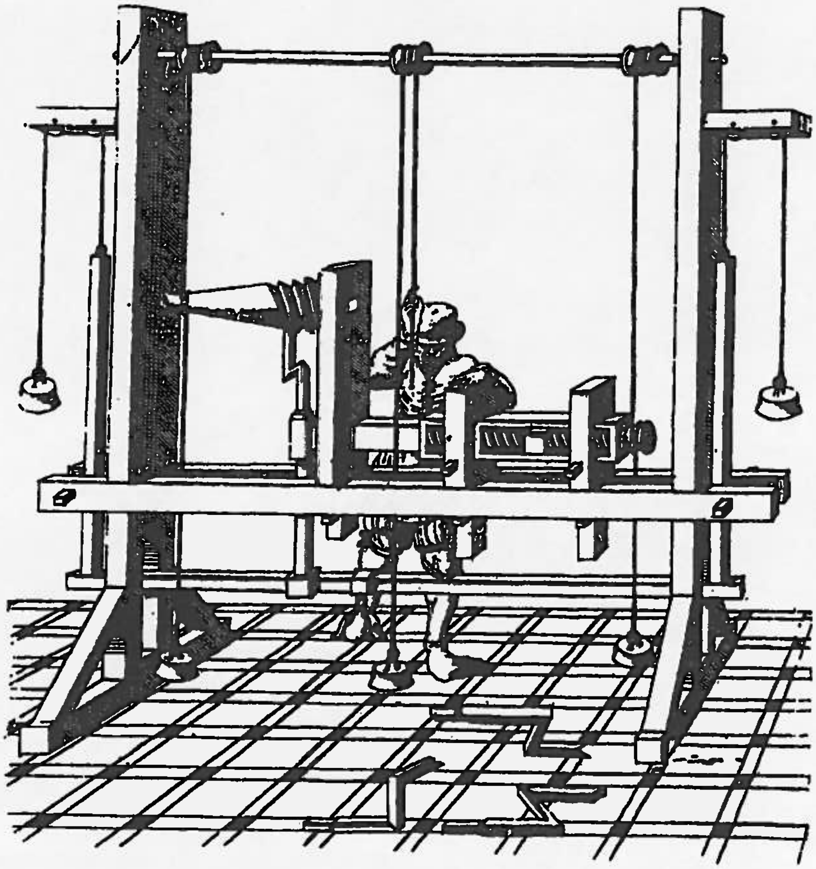

Figure 20. Jacques Besson's screw-cutting lathe, dating from 1579.

Source: From J. Besson. "Theatre des instrumens," Fig. 9. Lyons, 1579.

machine was semiautomatic in that the operator needed only to pull and release a cord. Its construction was complex and the lathe was probably not widely used (Woodbury, 1972, p. 57).

Instrument making in the sixteenth and seventeenth centuries was an art, not a standardized technique. Most improvements were the result of serendipity and trial-and-error searches. Learning and training took place mostly through apprenticing and informal contact. Mechanics had to build their own parts, and often the gap between the visionary who saw what *might* be done and the craftsmen whose material and tools limited what *could* be done was too wide to be bridged. The most famous of these visionaries was of course Leonardo Da Vinci, whose mechanical brilliance was on a par with his other talents. Leonardo left us with 5,000 pages of unpublished notebooks, many of which dealt with machinery. Yet the Last Supper notwithstanding, Da Vinci's creativity produced few free lunches, and few of his technical insights were realized in his lifetime.[10] Nor were the equally prophetic technical dreams of Leonardo's precursor, Francesco di Giorgio (1439–1502). As we shall see, the Industrial Revolution became possible when mechanics and machine tools could translate ideas and blueprints into accurate and reliable prototypes. Until then, instruments and tools were handmade, expensive to make and repair, and limited in their uses.

The period 1500-1750 is better known for its scientific achievements than its technological breakthroughs. The interaction between the two is the subject of an extensive literature, which cannot be done justice to here. What is striking, however, is that during the Renaissance, the classical dichotomy between thinkers and makers had all but disappeared in Europe, whereas the modern distinction between scientist and engineer had not yet appeared. Many scientists made their own instruments and contributed to the solution of practical problems associated with their manufacture. Galileo built his own telescopes and supplemented his salary as a professor at the University of Padua by making and repairing instruments. In England, Robert Hooke, the brilliant and eccentric physicist and biologist, pioneered the use of balance springs for watches and invented the Hooke's joint, an elegant device used for power transmission. Together with Robert Boyle, one of the most versatile scientists of his age, he produced a superior air pump, originally invented by another scientist of fame, Otto von Guericke. The physicist and mathematician Christiaan Huygens invented the pendulum clock and was one of the first to suggest an engine using an internal combustion chamber, for which he wanted to use gunpowder. Gottfried Leibniz worked on a wind-driven pump to remove water from mines in the Harz mountains. Even Isaac Newton, despite his professed (and unusual) lack of interest in technology, made a contribution to the perfection of the marine sextant, and was deeply interested in the problem of determining longitude at sea (Merton, 1938, pp. 172–73).[11] Thus, scientists may have been more important to technological change than science itself. All the same, their role was not decisive. The number of truly important technological breakthroughs

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[10] Not all of Leonardo's brilliant ideas were of academic interest only. His invention of mitred gates, fitted with small wickets for letting the water through, was applied to the Milan canal, and then to the Exeter canal in 1564.

[11] Historians of technology refer to seventeenth-century science as "experimental philosophy," an oxymoron that nicely captures the essence of advances in knowledge in those years. As late as the closing years of the eighteenth century, the physicist Count Rumford asserted, with some exaggeration, that "invention seems to be particularly the province of men of science" (cited in Hall, 1967, p. 115).

that the world owes to men renowned for their scientific contributions is not large (Kuhn, 1977, p. 142).

The Renaissance and the baroque period also witnessed the beginning of the application of mathematics to engineering in a variety of areas. During the Middle Ages, Europe had made few major contributions to mathematics. The Arabs adopted and perfected the decimal numeral system that still (unjustly) bears their name. They learned algebra from India and preserved and extended classical geometry. In the later Middle Ages the Europeans first saw, then learned, then imitated, then applied, then improved, then eventually took over the field, so that modern mathematics is by and large a European product. Mathematics was discovered to be useful to all economic activity, not just to engineering. The use of Arabic numerals was first introduced to Europeans by Leonardo Fibonacci of Pisa, whose *Liber Abaci* was published in 1202. The system caught on slowly, but it had enormous advantages for accounting, measuring, and calculating, and it was doubtless instrumental in the development of double-entry bookkeeping, which appeared in the middle of the fourteenth century.[12] Italian boys aspiring to become merchants had to attend the *scuola d'abbaco,* or schools of arithmetic (Swetz, 1987, p. 20). It soon became clear that mathematics was useful in more than just accounting. In the fifteenth century, Italian mathematicians showed how navigation could be aided by mathematics and Venice created a university chair of mathematics devoted to navigation. Niccoló Tartaglia, a mathematician living in the first half of the sixteenth century, dispensed mathematical advice to military engineers, surveyors, ore assayers, and merchants. Simon Stevin, a Flemish engineer, suggested in 1585 the use of what was to become known as the decimal point. About a decade later the Scottish mathematician John Napier discovered logarithms, making business calculations such as compound interest easy and accurate. William Oughtred, the Rector of Albury in England, invented the slide rule in 1621. At about the same time a Dutch mathematician, Willebrord Snell, developed the technique of trigonometric triangulation, which proved invaluable in determining distances and revolutionized mapmaking. Twenty years later, Blaise Pascal built a machine that could add and subtract, though his machine, like Leibniz's (which could also multiply and divide), remained too expensive to be practical. John Graunt, an English merchant, published the first life tables in 1662, and should be considered the founder of demography. Soon afterwards

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[12] The papers of the merchant of Prato, who after his death in 1410 left his estate (including his papers) to his hometown, include an astonishing amount of accounting material, including 500 account books that bear witness to the usefulness of the decimal system (Burstall, 1965, p. 112).

the English political arithmeticians William Petty and Gregory King pioneered the idea of observing a society through aggregate statistics.

The main applications of mathematics were in mechanical engineering. Mathematicians and engineers discovered that they needed each other. Mathematics was needed in measurement, civil engineering, ballistics, optics, navigation, and hydraulic systems.[13] Clockmakers wanted to know the optimal shape of the teeth on gear wheels that would minimize friction: the mathematicians Ole Roemer and Christiaan Huygens were able to show that the epicycloid was the curve satisfying this condition. In other areas, such as shipbuilding and machinery, the application of mathematics was more difficult, because much of the mathematics still needed to be developed. Galileo's development of mechanical physics and the later invention of calculus were necessary for those further advances. From the viewpoint of the history of technology, Galileo is particularly important because his theory of mechanics and concept of force lies at the basis of all machines. Until Galileo, the idea that general laws governed all machines was not recognized; each machine was described as if it were unique. Galileo realized that all machines transmitted and applied force as special cases of the lever and fulcrum principle.

As Cardwell points out, Galileo's theory of mechanics is interesting to the economist because the concept governing it is one of efficiency: "The function of a machine is to deploy and use the powers that nature makes available in the best possible way for man's purposes . . . the criterion is the amount of work done—however that is evaluated—and not a subjective assessment of the effort put into accomplishing it" (Cardwell, 1972, pp. 38–39). In the writings of Galileo, the leading scientist of his time, economic efficiency is linked with science. In *Motion and Mechanics*, he wrote that the advantage of machines was to harness cheap sources of energy because "the fall of a river costs little or nothing." In this he differed radically from his inspiration, Archimedes, and this difference between the two scientific giants who established the science of mechanics epitomizes the difference between classical and early modern society.

The period between 1500 and 1750 was thus one of technological development, but not one of revolutions. Considering the handicaps and obstacles that new technology faced in this period, it is surprising that the process did not grind to a halt altogether. As noted, the great discoveries may have been a substitute for technological frontiers: the challenging and possibly enriching opportunities lay over-

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[13] "Mechanics is the paradise of the mathematical sciences, because it is in mechanics that the latter find their realization . . . when none of the mathematical sciences can be applied, there is no certitude," wrote Leonardo (cited in Bertrand Gille, 1969, pp. 135–36).

seas. Moreover, the effects of the Reformation on the rate of technological progress were probably on the whole negative. That Protestantism itself was conducive to technological changes is doubtful. What matters to innovation is not only what one believes per se but to what extent society tolerates deviation and nonconformism (Goldstone, 1987), an issue to which I shall return in Part III. The Reformation, and its natural sequel the Counter-Reformation, made Europe a more bigoted place than it had been since the Crusades: Giordano Bruno was burned by the Catholic Inquisition, Miguel Servetus by its Calvinist counterpart in Geneva. Throughout Europe in the sixteenth- and early seventeenth centuries, the authorities' patience for people who thought for themselves and were critical of dogma was wearing thin. This pressure to conform slowed down technological change, though it is difficult to assess to what extent. In southern Europe, which came increasingly under the domination of the reactionary power of the Counter-Reformation, the climate for technological creativity changed for the worse.[14] Moreover, religious differences helped trigger wars that destroyed some of the most active centers of technological change in Europe, especially in the southern Netherlands (1568–90) and most of Germany (1618–48). Europe's ability to maintain its momentum, despite worsening circumstances, serves as a testimony to the resilience of the forces of technological progress. If Antwerp and Augsburg were destroyed, there was always Amsterdam and London.

Between 1500 and 1750 important changes in the form of industrial organization occurred in Europe, and these changes are likely to have affected the rate of technological progress. The driving force in these changes was the de-urbanization of industry. Cities were unhealthy places, plagued by sieges, epidemics, fires, overcrowding, poor water supply and sewage, and consequently high mortality rates. During the Religious Wars, many cities were besieged and sacked. The poor quality of life and short life expectancy in cities raised urban wages relative to the countryside, since towns had to continue to attract migrants. Another cause behind manufacturing's move to

[14] Around 1588, Giambattista della Porta constructed in Naples a successful incubator for hatching eggs. His innovative proclivities drew the wrath of the Holy Inquisition, who threatened to persecute him as a sorcerer. Della Porta wisely gave up his experiments. They were later resumed by the Dutchman Cornelis Drebbel and the Frenchman René Réaumur in societies where nonconformist ideas were better tolerated. France became less tolerant during the reign of Louis XIV, and many technologically skilled Huguenots emigrated. Among them was Denis Papin, who became Huygens' assistant in Holland and who made a fundamental contribution to the invention of the steam engine, as we shall see.

the countryside was the tight corporate structure of craft guilds, which restricted entry and imposed strict rules on the quality and price of output. It may well be the case that by the sixteenth-century town guilds had begun to stifle technological progress to protect their monopolistic position and vested interests. There are many documented cases of the authorities trying to suppress innovations in established industries, doubtlessly instigated by lobbies of vested interests. We shall return to this phenomenon of resistance to technology in Part III.

The stifling environment of Renaissance and baroque cities should not be exaggerated. Many cities, such as Leyden, had no guilds at all, and putting-out organization was by no means confined to the countryside. Design, finishing, marketing, and the production of custom-made upmarket goods remained largely in urban areas. But in town after town complaints surged that manufacturing was hurt by low-cost rural competition. As manufacturing in urban areas became more expensive, industry discovered the countryside. For goods whose production required relatively low skills, so that cheap and unsupervised labor could be profitably employed, rural workers in slack seasons were gradually recognized as an efficient source of labor. Much of this rural industry was organized by urban entrepreneurs who broke the production process into simple discrete stages and gradually developed a division of labor despite the dispersion of production sites. The rural-cottage industries were capitalistic, integrated into world markets, and devoid of the tight controls and regulations of urban industries.

The effect of this transformation on technological change has not been much explored. In the Middle Ages and the early Renaissance, cities, by multiplying human contact and facilitating the exchange of information, had been important in generating and diffusing technology, but by the sixteenth century this positive effect came to be dominated by the ability of organized vested interests to throttle new ideas. By removing much of industry from the cities, the guilds were faced with a source of competition that weakened their conservative influence. Some technological improvements clearly catered to the new modes of production: the stocking frame was widely adopted in rural cottages, new and superior spinning wheels were designed, and the flying shuttle, invented by the Englishman John Kay in 1733, increased the productivity of the domestic handloom weaver, who by that time was also most likely a rural resident. Above all, rural industry in many areas was the first attempt toward something akin to mass production. Although mass production without standardization and supervision had its limits, the merchant-entrepreneurs who

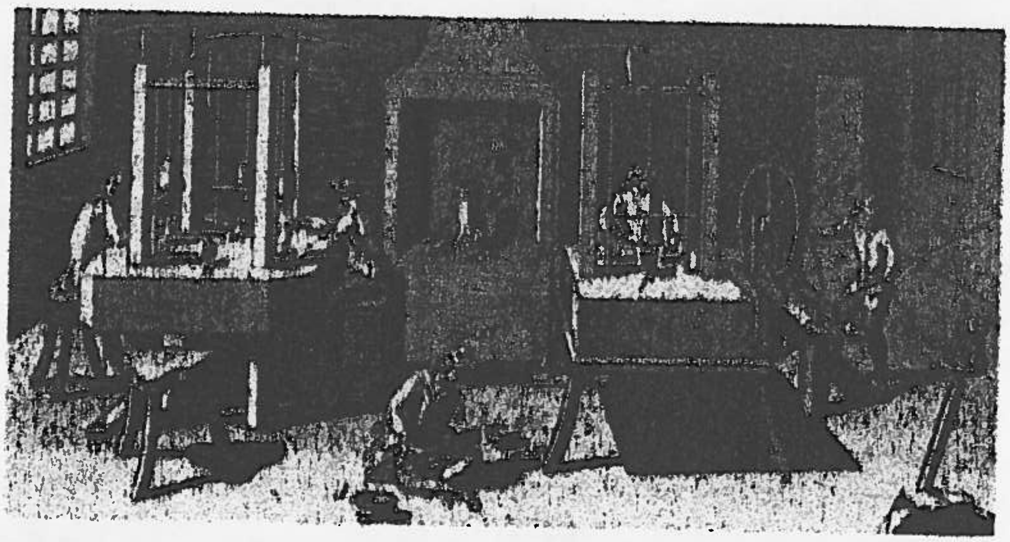

Figure 21. Pin factory dating from the time of Adam Smith. Smith used the pin factory as an example of the advantages of the division of labor. *Source:* Réaumur, *L'art de l'épinglier,* 1762.

ran the putting-out system increasingly realized the potential of cheap goods produced on a large scale, and learned to appreciate the profits inherent in cost-reducing technological advances.

The rise of nation-states between 1450 and 1750 also had important effects on technology. Although government officials rarely participated directly, many governments adopted policies that encouraged new technology. The objectives of these policies were, of course, frequently political and military, such as the design of fortifications, the casting of cannon, and the construction of men-of-war. Yet, in this period a mercantilist outlook led governments to follow an active industrial policy. States increasingly employed and subsidized engineers, and awarded monopolies, patents, and pensions to inventors deemed to have made important contributions to the welfare of the realm. When a nation felt left behind, it sometimes made a deliberate effort to catch up. The most famous example of government-inspired technological diffusion is Czar Peter the Great's stint as a carpenter in a Dutch shipyard. More than 200 years earlier, however, the czars were already sending for architects, miners, printers, and metal workers from the West. Similarly, King Gustav Adolph of Sweden invited the Dutch industrialist Louis De Geer, a Walloon by birth, to set up blast furnaces in Sweden, which—thanks to Sweden's high-quality ores and large forests—soon became a leading iron producer. These initiatives were not confined to the peripheral areas of Europe. The Lyons silk industry was founded when Louis XI enticed some Italian craftsmen to settle there, and the Sforza family attracted some of the best engineers of the time to work in Milan in the first half of the sixteenth century.

Some European governments discovered that protecting the property rights of the inventor encouraged technological change. The idea of granting an inventor a temporary monopoly position through a patent to reward inventive activity emerged from customs in mining activity. Mining contractors were awarded monopoly rights over discoveries of new mineral resources. These arrangements were subsequently adopted in other activities, such as grain milling, and eventually applied to new inventions. This custom appears in northern Italy in the first quarter of the fifteenth century. In 1460, the Republic of Venice granted two inventors a privilege stating that no one could reproduce their inventions without their permission. In 1474 a formal patent system was enacted in Venice, the preamble of which noted that if "provisions were made for the works and devices discovered by men of great genius, so that others who may see them could not build them and take the inventor's honor away, more men would apply their genius . . . and build devices of great utility to our commonwealth" (Kaufer, 1989, p. 5). Although few patents were actually awarded in Venice, its example was followed widely and by the middle of the sixteenth century the idea had penetrated much of Europe.[15] The most effective and famous patent law was the Statute of Monopolies, in England, passed in 1624. States also sponsored scientific societies, such as the Royal Society in Britain (chartered 1662) and the Académie Royale des Sciences in Paris (1666). These societies soon gravitated toward pure science, and the more important societies from the point of view of "facilitating the manual arts" (as Robert Hooke, one of the founders of the Royal Society, put it) were private.

Despite the absence of macroinventions, then, the late Renaissance and baroque periods were ages in which Western society became permeated with technology. As Bertrand Gille (1969, p. 146) points out, everything about the Renaissance was technological, including its art and its political philosophy. Medieval natural philosophy had pictured the universe primarily through biological metaphors. These organic images gradually yielded ground to a more mechanistic approach. Philosophers of the period increasingly adopted the view that technology was inherently virtuous and that knowledge of nature should be converted into control over nature for the purpose of increasing material production. Although such views were already implicit in medieval times, they are expressed with ever increasing

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[15] According to Bertrand Gille (1969, p. 146) more patents were granted in Germany in the sixteenth century than in the eighteenth century.

clarity and vigor in the sixteenth- and seventeenth centuries.[16] Europeans were becoming conscious of the infinite possibilities that technology promised for human welfare, and realizing that by accepting change as a way of life, they could have access to a never-ending stream of free lunches.

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[16] The German physician Paracelsus argued in the 1530s, for instance, that God desires that "we do not simply accept an object as an object but investigate why it has been created. Then we can . . . cook raw food so that it tasteth good in the mouth and build for ourselves winter apartments and roofs against the rain." Francis Bacon, writing three quarters of a century later, insisted that knowledge should be made useful, and science be put in the service of technology in the quest for an "empire of man over nature." Galileo hoped that his practical philosophy would help "in the invention of an infinitude of artifices which would allow us to enjoy without trouble the fruits of the earth and all its commodities" (cited in Klemm, 1964, pp. 144, 174, 180).