THE LEVER OF RICHES

Technological Creativity and Economic Progress

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CHAPTER FIVE

The Years of Miracles: The Industrial Revolution 1750-1830

By 1750, Europe had consolidated its technological superiority over the rest of the world. Front the Bosporus to Tokyo Bay, the Oriental empires were falling behind by isolating themselves from the West and experiencing a slowdown in their own technological progress. Some of theta, like India, were already coming under Western domination. Yet, it seems plausible that if European technology had stopped dead in its tracks-as Islam's had by about 1200, China's had by 1450, and Japan's had by 1600-a global equilibrium would have settled in that would have left the status quo intact, with few exogenous forces to upset it. Instead, the last two centuries have been a period of ever accelerating change, a disequilibrium of' epic proportions unlike anything that came before it. In two centuries daily life changed more than it had in the 7,000 years before. The destabilizing agent in this dizzying tale was technology, and Western technology alone. Of' course, technological progress did not start in 1750, and the difference between the period after 1 750 and the period before it was one of degree; but degree was everything. The effects of the gains in productivity allowed Europe to expand its population manifold in blatant defiance of Malthusian constraints; to provide Europeans with a quality of life incomparably higher than that of traditional societies; to extend, for a while, political control over most of mankind; and to reshape technology elsewhere in the European image.

In recent years, the concept of the Industrial Revolution has come under serious scrutiny. Authors such as ‚Jones (1988) have argued that there was little economic growth in Britain in the second half of the eighteenth century. Since it has been customary to identify the Industrial Revolution with growth of per capita income (see E. A. Wrigley, 1987, for a recent restatement), the implication seems to be that the concept of an Industrial Revolution is dispensable. Yet recent calls to ban the concept from our research papers and lecture notes seem misplaced, to say the least. The Industrial Revolution was not primarily a macroeconomic event that led to a sudden acceleration of the rate of growth, although growth eventually became its inevitable corollary. The identification of the Industrial

Revolution with economic growth suffers from a number of serious defects. First and foremost, by focusing on a per capita variable it glosses over changes in a ratio, per capita income, in which both the numerator (income) and the denominator (population size) were increasing more or less pari passu. As it happened, the years of the Industrial Revolution were years of rapid population growth, and per capita changes were swamped by demographic changes. Second, economic growth need not be a result of industrial change at all; it could be (and often was) rooted initially in agricultural or commercial developments. Third, per capital income is notoriously hard to measure accurately during a period in which the economy undergoes rapid changes in the way its markets operate. Commercialization implies that goods previously produced by households are now purchased on the market. Unless meticulous adjustments are made, these changes tend to bias the measures of economic growth. Furthermore, a second bias is introduced when technological change introduces new goods or improves the quality of existing ones.

Thus, even if aggregate statistics do not reveal a sudden leap, there is room for the concept of an Industrial Revolution (Mokyr, 1991). It is appropriate to think about the Industrial Revolution primarily in terns of accelerating and unprecedented technological change. In the words of T. S. Ashton’s (1948, p. 42) famous schoolboy, it was first and foremost a “wave of gadgets” that swept over Britain after 1760, a string of novel ideas and insights that made it possible to produce more and better goods and do so more efficiently. To return to the terminology introduced earlier, a clustering of macroinventions occurred, leading to intensified work in improvement and adjustment, and thus creating a complementary flow of microinventions. The result was a sharp increase in patenting activity. Patent statistics do not permit us to distinguish between radical and minor inventions. The propensity to patent varied widely from industry to industry, from location to location, and even from individual to individual (MacLeod, 1988, pp. 75-114). Yet dismissing the volume of patents altogether as an indicator of inventive activity is premature. The sharp increase in the rate of patenting after 1760 requires an explanation (Sullivan, 1989). Something profound changed in the role of technology in the British economy around this time, although it is yet far- from clear whether the rise in patenting was a response to perceived needs and opportunities or a consequence of’ deeper change, affecting the technological creativity of Britain as it whole.

The Industrial Revolution is usually dated between about 1760 and 1830. Britain is usually thought of as its locus, but a large part of the new technology was the result of work done in other European countries and later in the United States. The fruits of the Industrial Revolution were slow in corning. Per capita consumption and living standards increased little initially, but production technologies changed dramatically in many industries and sectors, preparing the way for sustained Schumpeterian growth in the second half of' the nineteenth century, when technological progress spread to previously unaffected industries. It is not easy to generalize about the kind of' technological change that occurred. Some scholars have proposed that the main feature of technological change in this period was the substitution of' inorganic for organic materials (E. A. Wrigley, 1987). Others try to define the Industrial Revolution as an increase in energy inputs, especially inanimate energy, and focus on steam power as the most significant advance (Cipolla, 1965a). Still others focus on the use of machines instead of' hand tools (Paulinyi, 1986). Yet these generalizations fail to do justice to the rich diversity of' progress in these yews. The growth of cotton at the expense of wool and linen, the improvements in the efficiency of waterpower, the development of' gaslighting, the advances in the machine tool industry, and the invention of food canning, to mention just a few examples, really share few common characteristics, save their ability to increase both the quantity and quality of the supplies of goods and services. As McCloskey (1981, p. 118) put it, the Industrial Revolution was not the Age of Cotton, or the Age of Steam; it was the age of' improvement. Yet improvement was not ubiquitous. Large sectors of' the economy, employing the majority of' the labor force and accounting for at least half of' gross national product were, for all practical purposes, unaffected by innovation before the middle of the nineteenth century. In services, construction, food processing, and apparel making techniques changed little or not at all before 1850. The reason sonre industries changed and others did not has little to do with either the demand side of the economy or the supply of raw materials and coal. “technological opportunities and constraints by and large determined where and when improvements were to occur.

During the Industrial Revolution, technological progress was usually the result of the joint and cumulative efforts of many individuals. A typical innovator in those years was it dexterous and mechan ically inclined person who became aware of a technical problem to be solved and guessed approximately how to go about solving it. The successful inventors were those who put the pieces together better than their colleagues, or those who managed to resolve one final stubborn difficulty blocking the realization of 'a new technique.

It is useful to divide the technological changes during the Industrial Revolution into four main groups: power technology, metallurgy, textiles, and a miscellaneous category of other industries and services.

POWER TECHNOLOGY

The protestations of some economic historians notwithstanding, the steam engine is still widely regarded as the quintessential invention of the Industrial Revolution. Its background was not purely British; it is more accurate to think of it as the result of an international joint effort. The basic idea for the construction of an atmospheric engine was based on the realization that an atmosphere exists. What seems today a commonplace insight was the fruit of the work of Evangelista Torricelli, a Student of Galileo's, and Otto von Guericke, the mayor of Magdeburg, famous for his experiment in which two teams of horses could not separate two hemispheres enclosing a vacuum.[The existence of an atmosphere and its pressure may well have been known to the Chinese, but what followed in the second half of' the seventeenth century was a typically European story. It occurred to many who had grasped the newly discovered phenomenon that if a vacuum could be created repeatedly, the force of atmospheric pressure could yield a novel source of power. The Marquis of Worcester, among others, suggested in 1663 a machine utilizing condensation for this purpose. The first known model was built in 1691 by Denis Papin, an assistant to Christiaan Huygens, who showed in a prototype how a piston could be moved up and down a cylinder using steam. Application to a useful purpose followed suit. 'T'homas Savery built the first working steam engine in 1698, though this device was really a suction pump that condensed steam in a closed vessel and sucked up the water by means of the vacuum. A different version was perfected in the first decade of' the eighteenth century by Thomas Newcomen, who, unlike Savery, used atmospheric pressure in a ma chine that was alternately heated and cooled, so as to create repeated vacua by condensation. The first economically successful engine, known as the Dudley Castle Machine, was installed in a coal mine near Wolverhampton in 1712. Newcomen's engine was far more complex and sophisticated than Papin's prototype, yet it was within the ability of the craftsmen of' the time and it was sate. It was powerful enough to pump water out of mines, and despite its awkward dimensions, its voracious appetite for fuel, and the difficulty early eighteenth-century mechanics had in achieving hermetic sealing, the Newcomen machine was widely adopted. Within a few years of- its inception, it spread to France, Germany, and Belgium, and by 1730 it was operating in Spain, Hungary, and Sweden and later in the American colonies. The machine solved drainage problems in the Cornish tin mines, as well as in the deep coal mines in the north of' England. But above all, it was the first economically useful transformation of thermal energy (heat) into kinetic energy (work).2

Yet the steam engine will forever remain associated with the name of,James Watt. The basic improvement that Watt introduced was to separate the condenser from the piston cylinder, so that the latter could he kept hot constantly. This separation greatly reduced the fuel requirements of the machine and permitted it to be used almost anywhere. Wait's ingenuity provided many further improvements oil the steam engine, including, steam-jacketing, to keep the cylinder hot; a transmission mechanism known as the "sun-and-planets" gears, which converted the reciprocating motion of the atmospheric engine to the rotative motion needed in textile mills and other industrial applications; and a parallel motion gear that allowed steam to be introduced alternately info both ends of the cylinder, thus creating it doubleacting engine that Utilized the push as well as the pull of the end of' its bean. 'I'll(- double-acting expansion machine used the steam above the piston to drive it down, but cut off the steam after the piston had moved part of the way in order to save fuel. As a result, fuel efficiency was raised from less than 1 percent in the Newcomer engine to around 4.5 percent in Watt's design. The principle of doubleacting engines had been known in Europe since the fifteenth cen tury, and used in pumps and bellows, but the steam engine was by far its most successful application (Reti, 1970). The utilization of the expansive power of steam was regarded by Usher (1954, p. 354) as the difference between an atmospheric and a genuine steam engine. Equally important was the "governor" for regulating the speed of engines, which foreshadowed twentieth-century feedback servomechanisms, which form the basis for cybernetics. The device consisted of two balls that were pushed outward when the speed of op eration increased and that lifted an arm attached to the valve in the steampipe. Similar automatic regulators had been applied earlier to windmills, but Watt's invention symbolizes the desire for full control and automation that increasingly permeated the techniques of the time.

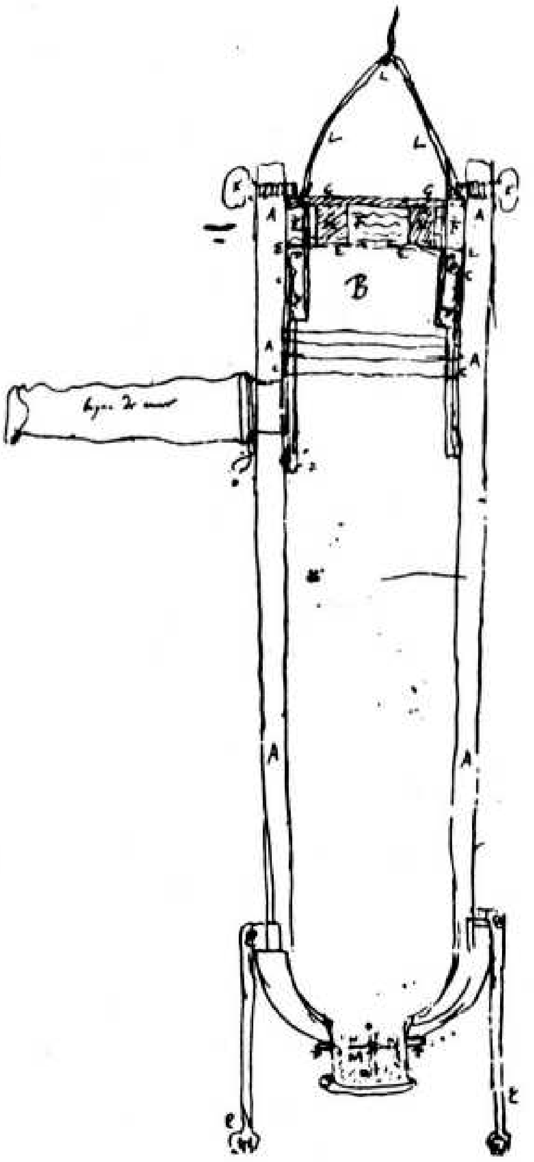

Figure 22. Rough sketch by Christian Huygens of his gunpowder-fueled internal combustion engine.

Source: Chr. Huygens, Oeuvres completes, 1763.

Watt's work, which combined inventive genius with a desire to cut costs, minimize wear and tear, and extract "the last drop of `duty' from the last puff of steam in his engine" (Cardwell, 1972, p. 93), was paradigmatic of the kind of mind that helped make the Industrial Revolution. Watt himself, in his oddly written third person autobiography, wrote that "his mind ran upon making engines cheap as well as good." The search for economic value in addition to functionality and beauty represents the culmination of a millennium of development of European technological rationality. Yet rationality meant nothing without technical ability, and Watt's mechanical talents bordered on the virtuoso. In short, in the history of power technology, Watt is comparable to, say, Pasteur in biology, Newton in physics, or Beethoven in music. Some individuals did matter. We should bear in mind, however, that Watt stood on the shoulders of Papin and Newcomen; of John Wilkinson, whose new boring machines supplied Boulton & Watt with cylinders of great accuracy; and of his partner Matthew Boulton, with whom Watt formed a classic inventorentrepreneur team (Scherer, 1984, pp. 8-31). The steam engine became a familiar sight in eighteenth-century Britain. It is now reckoned that close to 2,500 engines were built in the eighteenth century, of which about 30 percent were made by Watt, by far the largest producer (Kanefsky and Robey, 1980). The most important user of steam power was mining, with 828 engines in collieries and another 209 in copper and lead mines by 1800.

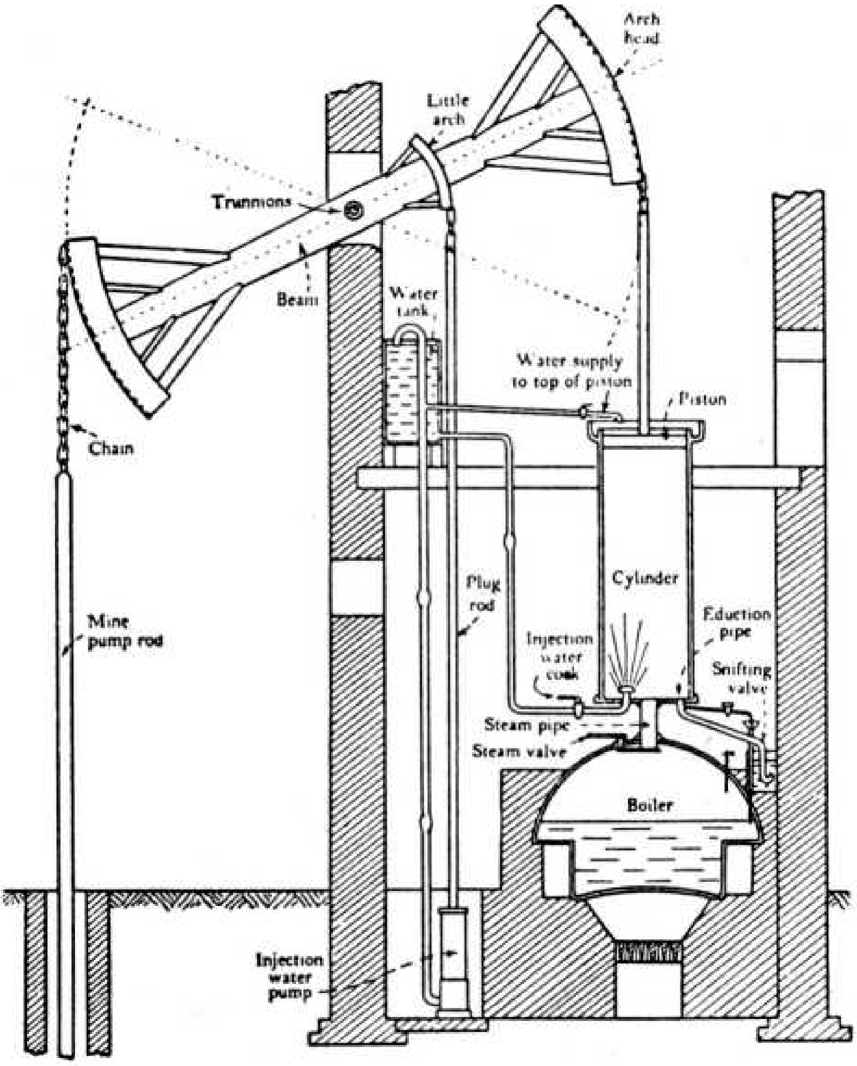

Figure 23. Diagram of Newcomen's atmospheric engine.

Source: From H. W. Dickinson. "A Short History of the Steam Engine," Fig. 7. Cambridge University Press, 1939.

Watt's patent expired in 1800, and a new genius applied himself to the construction of a revolutionary steam engine. Watt had felt that a high-pressure machine-already suggested by Savery-was too dangerous to be practical. But in 1802 another Englishman, Richard Trevithick, built a machine that created pressure ten times as high as the atmosphere. These high-pressure machines were smaller in size and more economical than Watt's engines. In the mines of Cornwall, high-pressure engines were applied with success to the beam engine pumps used for drainage, known as "Cornish" engines. Moreover, these engines could be placed on boats and horseless carriages. A steamboat prototype was built by the Marquis de Jouffroy in France in 1783 and by John Fitch and James Rumsay in the United States in 1787. It was made practical by the American Robert Fulton in 1807. Within ten years Fulton's boats were dominated by highpressure engines, pioneered in the United States by Oliver Evans (Hindle, 1981, p. 55). Meanwhile, the Watt low-pressure stationary engine also underwent improvements, and the two types existed side by side throughout the nineteenth century.

The next step in the development of steam power was compounding, that is, the use of the same steam in more than one cylinder, one of which is high pressure. In these engines, after the steam does its duty in the high-pressure cylinder, it is admitted into a larger cylinder, where it drives down a piston using the principle of expansions The first successful application of compound engines was made by Arthur Woolf in England in 1803. Compounding became practical only in 1845, when John McNaught (after whom the verb "Mcnaughting" was coined) perfected the process. The advantage of compounding was fuel saving: Woolf's compound engine raised fuel efficiency to 7.5 percent (compared to 4.5 percent in Watt's engines), and the sophisticated Corliss compound steam engine of 1878 had a thermal efficiency of over 17 percent.

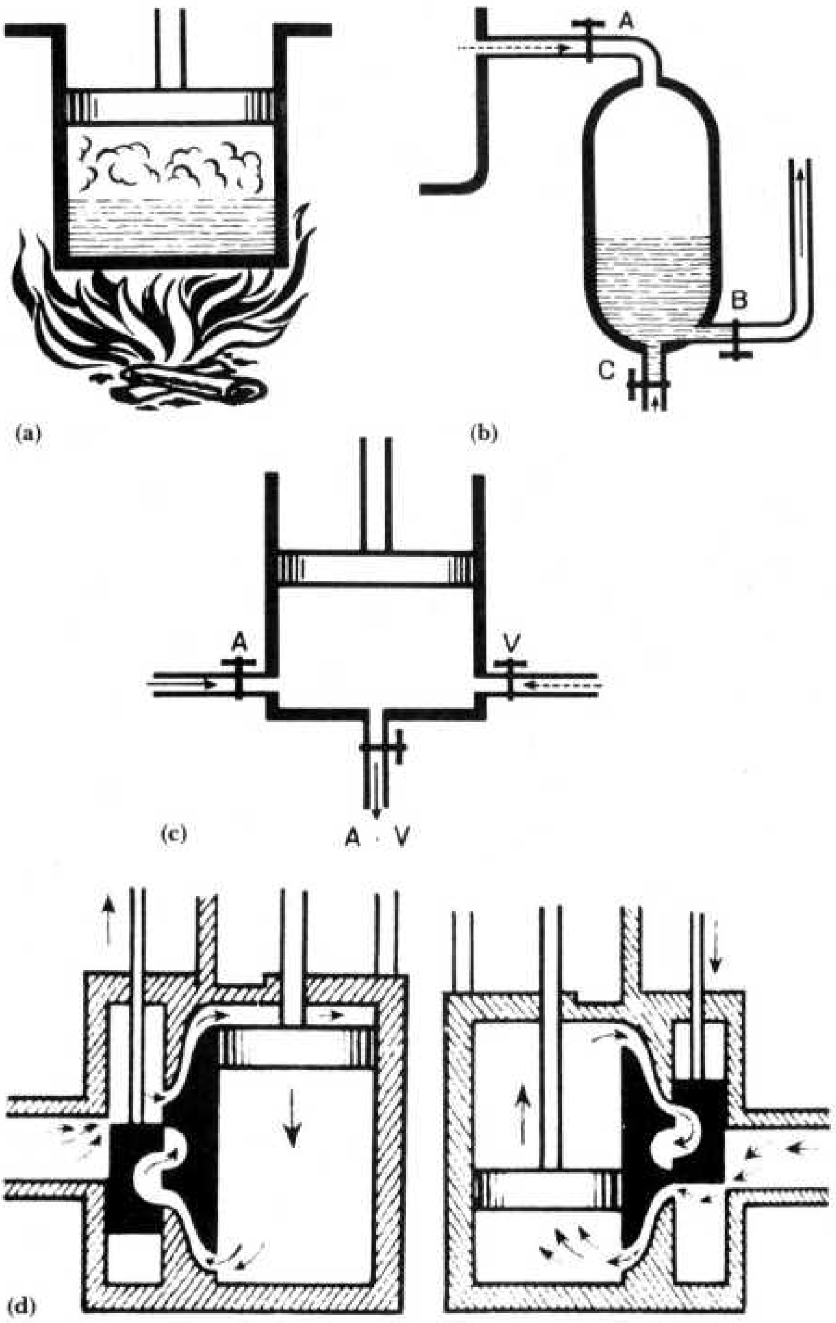

Figure 24. Principles of early steam engines: (a) Papin's prototype, (b) Savery's pistonless suction pump, (c) Newcornen's engine, and (d) Watt's doubleacting engine. The machine exploits the contrary motion of the piston and the slide-valve above it, with the steam entering alternately from the left and the right.

Source: Umberto F.co and G. B. Zorzoli, The Picture History of Inventions. © Gruppo Editoriale Fabbr: Bompiani Sonzongo Etas S.p.A.

The success of the steam engine preceded the establishment of a science that formalized the principles upon which it was based. In 1824, the Frenchman Sadi Carnot, upon observing a working steam engine and asking himself why high-pressure engines were superior, developed the kernel of what was later to be known as thernrodynamics. Carnot also maintained that “to take away England’s steam engines today would amount to robbing her of her iron and coal, to drying up her sources of wealth, to ruining her means of prosperity and destroying her great power” (cited in Cardwell, 1972, p. 130). Economic historians would probably disagree. The assessment of the contribution of the steam engine should not be based on the gross achievements of the steam engines, but on the marginal contribution of steam over its next best alternative.

That next best alternative was waterpower, still an important source of power in Britain in 1830, and the dominant source of energy in Switzerland and New England at that time. The gains that the steam engine provided relative to waterpower before 1850 were fairly small (von Tunzelmann, 1978, pp. 285-92), but this should not take away from the achievement of the people who made the Industrial Revolution. Indeed, it confirms it, because the slow diffusion of steam power in many places is explained by improvements in the efficiency of waterpower. In other words, the wide range of progress in power technology was responsible for the relatively slow growth of one specific technique. This was particularly true for the European continent and New England. The improvements in waterpower after 1750 were associated with constant improvements in the understanding of the theory of hydraulics. The most important advance was the breast wheel, which was introduced by John Smeaton in the 1750s and soon spread all over Britain. Breast wheels receive water at an intermediate point between the summit and the bottom of the wheel, and thus in a sense are a compromise between overshot and undershot wheels. The breast wheel was as efficient as the overshot wheel, but had the advantage that the wheel turned in the same direction as the flow of water in the tail race, which allowed it to work under flooding conditions. Smeaton’s work was improved by the introduction of the sliding hatch, introduced by John Rennie in the 1780s, which allowed the breast wheels to adapt to varying water levels. Later it was discovered that efficiency could be further improved by setting the blades such that they entered the water at an angle of 45 degrees to the surface (Daumas and Gille, 1979a, p. 28). Like the engineers working on steam engines, their colleagues working on the “traditional” technology were determined to extract as much energy as possible from every moving drop of water. In the nineteenth century, waterwheels were increasingly made of’ iron parts, which reduced wear and tear. Smeaton, Rennie, and their colleagues were practical engineers, not scientists, and Smeaton was known for his distrust of scientific theory. This distrust was not altogether misplaced: it was not until the 1750s that scientists realized that different principles applied to the gravity-driven wheels of overshot mills and the impulse-driven wheels of undershot mills. For a long time, practical men without formal training in hydraulics kept snaking the important improvements.

Across the Channel, French engineers were equally successful. Jean Charles Borcla was the first to attack the theoretical problems of waterpower in 1766, though his work was too abstract to he of imme diate use and was not recognized until after 1810 (Reynolds, 1979). Jean Victor Poncelet used Borda's ideas to modify the undershot waterwheel to build the famous Poncelet waterwheel (1823), which used curved blades and fed the water through an inclined haute. The so-called column of water or water-pressure engine, extensively employed on the Continent, ingeniously combined the idea of it Newcomen engine with the pressure of' water (rather than the atmosphere). Waterpower technology was further advanced by the invention of' the water turbine. The idea originated in the eighteenth century with Leonhard Euler, the Swiss mathematician, who, together with his son Johann, showed that by using the force of water coming out of the varies of a waterwheel, the entire energy of' the flow could be converted into useful work. The difference between this concept and the waterwheel is that in the latter the water does not move relative to the buckets or vanes, while in the former the power is derived from the water flowing rapidly through curved passages driving the engine. The practical implementation of the idea took many years of tedious work by many engineers (mostly in France), culminating in the success of the Frenchman Benoit Fourneyron in 1837. The turbine was introduced into the New England textile industry and "delayed for decades the dominance of' steam power in that industry" (Rae, 1967b, p. 338). By this tittle, advances in waterpower technology had been so impressive that one historian notes that in theory, and to a large extent in practice, engineers had complete command over waterpower (Cardwell, 1971, p. 184). Nonetheless, the utilization of' waterpower remained constrained, not so much by the water mills themselves as by the lack of a scientific understanding of watershed hydrology and the requisite data on rainfall (Gordon, 1985).

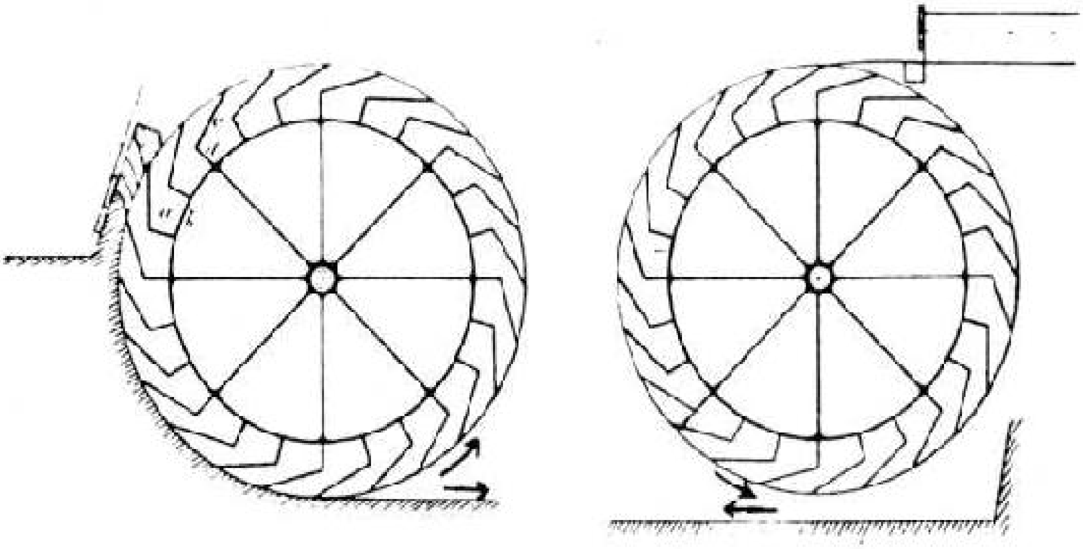

Figure 25. Comparison of high breast waterwheel (left) and traditional Waterwheel (on the right). Note that in the breast-wheel the water moves in the same direction as the wheel, in contrast with the traditional wheel.

Source: F. Redtenbacher, Theorie and Ban der Wasserrader (Mannheim: Friedrich Bas- serman, 1846), p1. 1, Figs. 5-6.

The Industrial Revolution was an age of' power technology, and the prospects must have seemed unlimited. The economic impact of the steam engine during the Industrial Revolution may not have been initially as large as Carnot thought, but in the second half of the nineteenth century steam power penetrated every aspect of economic life in the Western world and beyond. In conjunction with other inventions, power technology created the gap between Europe and the rest of the world, a temporary disequilibrium that allowed the Europeans to establish global political and military domination.

METALLURGY

Prior to the Industrial Revolution, metallurgy had been an empirical and experimental art in which gifted amateurs and semiprofessionals tried to solve complex chemical and physical problems that baf fled those engaged in the day-to-clay manufacture of metals. “their success is a monument to their determination to produce materials that satisfied their needs better and more cheaply. Among these materials, iron ruled supreme. There were no substitutes for it in terms of durability, versatility, and malleability. We have seen that the later Middle Ages witnessed the development of cast iron, which has a relatively high carbon content and a low melting point. It was brittle and hard, and could therefore not he shaped using the blacksmith’s traditional tools, but it could be cast to make pots, ovens, and cannon. Most products, including machine parts, nails, locks, and tools, needed to be shaped in forges, and for these wrought iron was needed. The process of turning pig iron, the output of blast furnaces, into wrought it-on remained it major bottleneck in the metal industry. During the eighteenth century an extensive search was conducted into this problem in Britain. The Wood brothers pioneered the socalled potting process, Using crucibles, or “pots,” to heat the pig iron (Hyde, 1977, pp. 83-88). The problem’s ultimate solution by Henry Cort in 1784 was it skillful combination of a number of’ elements, such as the coal-burning reverberatory furnace that had been used in glassinaking for it long time, and the rolling of’ heated metal using grooved rollers. Cort’s puddling and rolling process was typical of many great inventions of the Industrial Revolution in that it was the culmination of it dispersed and drawn out search for the solution of a difficult but economic-ally’ important problem. After several improvements in the late 1780s, Cort’s process took the British world of metallurgy by storm. The small independent forge, until then the source of’ all wrought iron, vanished, to be replaced by the larger puddling furnaces. The supply of high quality and cheap wrought iron grew dramatically, making iron almost literally the building block of the Industrial Revolution.

The eighteenth century also witnessed another invention comparable in fame: the use of’ coke in blast furnaces. Coke is purified bituminous coal, and its use in smelting was pioneered by Abraham Darby. Coke had been employed earlier in industry, but its use in blast furnaces dates from about 1709. New research on the iron industry has refuted the widespread myth that coke smelting was triggered by a scarcity of wood, and that the diffusion of, the invention was impeded by the secrecy of the ironmaster’s family (Flinn, 1978; Hyde, 1977, pp. 25-29). The simple problem was that for a long time coked iron contained silicone, which made it more costly to convert coked pig iron into wrought iron (Fylecote, 1976, pp. 108-9). The growth of coking after 1750 has been explained by further technological progress, especially I)arby’s son’s success in remelting the pig iron in a so-called foundry furnace, to remove the silicone. Other improvements included the making of cokes in closed ovens shaped like beehives, and the replacement of old-fashioned bellows by new waterpowered blowing cylinders, invented around 1760 by the versatile John Smeaton. Between 1760 and 1790, coke replaced charcoal in British iron smelting and was gradually introduced on the Continent. Blast furnaces became bigger and more efficient, pro ducing better-quality iron at lower prices. Another major breakthrough was achieved by the Scotsman James

Neilson, who hit upon the idea of using the blast furnace's own gases to preheat the air inside (1829). The hot blast procedure was cheap to install and simultaneously reduced fuel requirements by a factor of three. It created temperatures hot enough to use fuels other than coked bituminous coal, such as anthracite. Between 1828 and 1840, Scottish producers experienced a cost-reduction of almost two thirds, but as the technique spread through Britain, pig iron prices fell, and profits with them (Hyde, 1977, pp. 151-52). It was this process that made it possible to exploit the black-band iron ore deposits in Scotland and allowed Scotland to compete with the Black Country (in the English Midlands) and Wales in pig iron production.

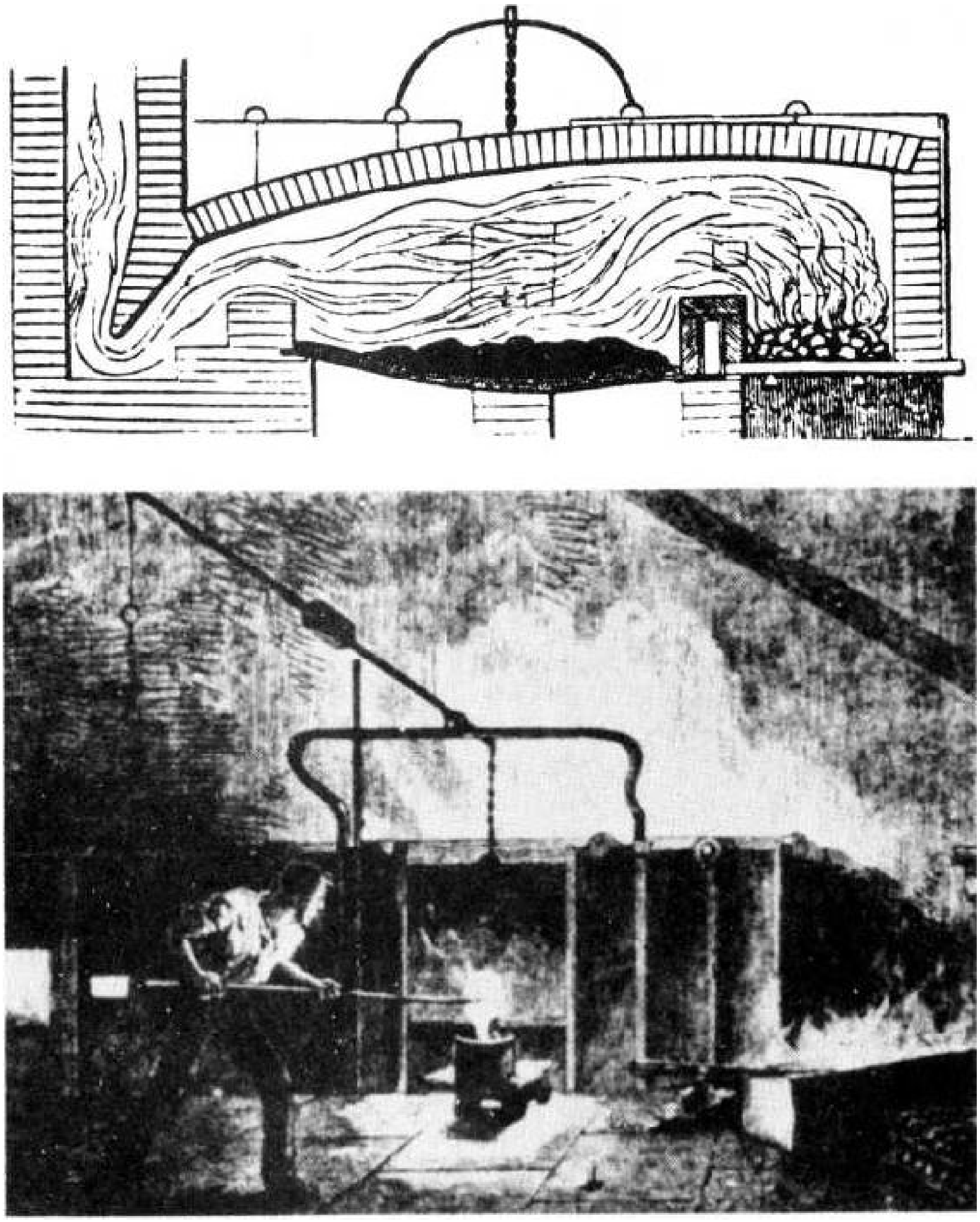

Figure 26. Section of Cort's puddling furnace, which produced wrought iron.

Source: Archibald Clow and Nan L. Clow, The Chemical Revolution, Batchworth Press.

The product that resisted innovation most stubbornly was steel. Chemically, steel is an intermediate product, hallway between the almost carbonless wrought iron and high-carbon pig iron. Steel can be made from iron by adding carbon to low-carbon wrought iron (cementation or carburization); by removing carbon from high-carbon cast iron (decarburization); or by mixing high and low carbon scraps of iron together (cofusion). A fourth process produced steel directly front ore by packing it in crucibles with pieces of special wood. This last product, known as zvootz steel, originated in India (in Hyderabad). The desirable physical properties of* steel (resilience, tenacity, and flexibility) made it ideal for razors, weapons, shears, springs, and machine parts, but it was prohibitively expensive. In the West, steel was produced by cementation, it process first known in Asia Minor around 1000 B.C. The production of’ this “blister steel” entailed “baking” the wrought iron by heating it in direct contact with charcoal and hammering it for long periods to spread the carbon through the metal. The blast furnace offered new opportunities for making steel by refining the high-carbon cast iron, or by immersing pieces of low-carbon wrought iron in molten cast iron. Furthermore, ores high in manganese allowed it better control of the carbon removal, so that some residual of carbon could he left in the iron. By the seventeenth century, Europeans had learned that steel could be improved by remelting and hammering small pieces of it at very high temperatures, thus spreading the carbon somewhat more evenly. The production of’ high-quality steel was perfected in about 1740 by Benjamin Huntsman, who used coke and reverberatory ovens to generate sufficiently high temperatures to enable him to heat blister steel to its melting point. In this way he produced a crucible, or cast, steel that was soon in high demand by instrument- and clockmakers. The importance of crucible steel was that it could be cast, and eventually the production of larger ingots became possible through the coordinated operation of’ many crucibles. The German steel manufacturer Alfred Krupp pioneered these techniques in the casting of” steel cannon. His six-pounder was one of the great sensations of the Crystal Palace Exhibition of 1851, as was a gigantic steel casting weighing 4,300 Ib. Yet steel remained too expensive to be of widespread use during the critical years of the Industrial Revolution. Wrought iron rather than steel was the main material until 1860.

TEXTILES

The central technical problem in textiles was that of spinning. Since time immemorial, the crucial operating part in the spinning process had been the human finger, the thumbs and index fingers of millions of women who gave the raw material in the rovings the “twist” that made it into yarn. The spinning wheel increased the efficiency of the spinner’s work, but did not replace the human finger as the tool that transformed the material. The search for it replacement for human fingers in cotton spinning was taken up by Lewis Paul, an Englishman who pioneered the idea of’ using rollers to replace the fingers in drafting out the fibers. His patent was taken out in 1738, but it is Richard Arkwright to whom the mechanization of spinning is usually credited, more than 30 years later. Arkwright's machine, the "throstle" or "water frame," differed from Paul's in one respect: he used two pairs of rollers moving at different speeds and separated by a distance about equal to the length of the longest fiber to be spun. The result was that Arkwright's machine worked, whereas Paul's did not. The water frame was incapable of spinning the finer yarns, as these would have snapped when they were wound on the bobbins.

The water frame was complemented by another invention, the spinning jenny, which was patented it year after the throstle, but actually invented in 1764. Its inventor, James Hargreaves, reputedly hit upon the idea after watching a spinning wheel fall on its side and continue to spin for it few more seconds. He realized that it was possible to "draft against the twist," that is, to impart the twist not by the movement of the fingers but by the correct turning of the wheel itself. The jenny twisted the yarn by rotating spindles that pulled the rovings from their bobbins, with metal draw bars playing the role of human fingers guiding the spun yarn onto the spindles by means of a faller wire. Instead of the single spindle turned by the spinning wheel, Hargreaves' machine used many spindles and thus allowed a large number of threads to be spun at the same time. The quality of the yarn was rather uneven, however, and it was suitable Only for weft. Moreover, the jenny was an extremely uncomfortable machine to work with, forcing adult spinners to bend over nearly double (Hills, 1979). Combining the throstle's rollers with the multiple spindles of the jenny led to the mule, the ultimate spinning machine, invented by Samuel Crompton in 1779. One of the most famous inventions of all times, the mule consisted of a carriage that was driven back and forth. In so doing, the spindles mounted on it turned quickly and together with the rollers imparted the twist on the yarn, which could then be wound on bobbins. At no stage was the yarn subjected to much strain, and thus the chances for breaking were much reduced. The mule could thus make cotton yarn that was both cheaper and finer, stronger, and more uniform than hitherto. As a result, cotton became a growth industry the like of which no one had ever seen. Until Crompton, the cotton yarn spun in England was not strong enough to serve as warp and hence cotton was used in combination with other yarns. The mule made all-cotton cloth possible. It was especially suitable for finer yarn; coarse yarns continued to be spun by jennies for a long time, as they were cheaper and could be readily used in domestic industry. Spinning jennies, water frames, and mules were all tried in domestic industry, but soon the factory was found to be a more congenial location for the new spinning technology (Landes, 1986). Nonetheless, it is not warranted to associate the Industrial Revolution with the rise of the factory system; domestic industry, too, experienced some measure of technological progress, some of it in symbiosis with the factories.

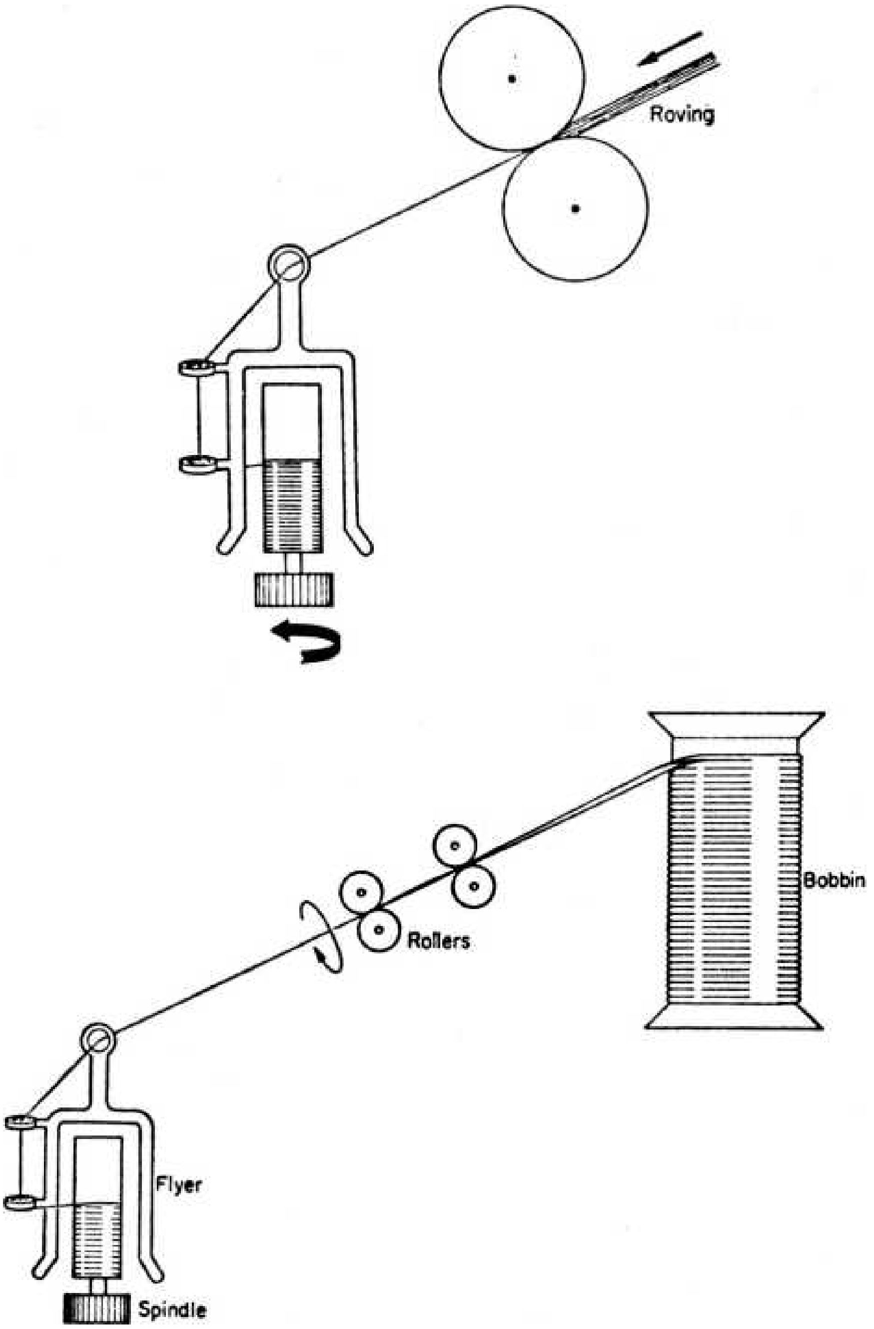

Figure 27. The mechanical principle behind the Wyatt-Paul spinning machine, and Arkwright's throstle.

Source: ll. S. L. Cardwell, Turning Points in Western Technology, Science History Publications.

Modifications in spinning were subsequently introduced, but the main breakthroughs had been achieved by 1780. Application of steam power to the new machine followed in the 1780s, although animaland waterpower dominated in the early years. The self-acting mule, patented by Richard Roberts (an improved version was brought out in 1830) was a triumph of British engineering, in the words of Mann (1958, p. 290) "an almost perfect machine." The self-actor made the movements of the carriage which pulled and wound the yarn automatic, so that the operator who moved it and put the faller wire in place became unnecessary. Yet despite its obvious advantages, it was adopted so slowly that the patent authorities decided to extend the patent by another seven years. One reason seems to have been that self-actors were expensive, and sources of long-term credit for fixed capital were scarce. Second, the self actors were better suited for coarse (low-count) yarns until about 1860. Third, the structure of the labor force established on the common mules, in which a male "minder" carried out certain managerial and supervisory functions, may have had a momentum of its own as the minders had an obvious interest to resist the introduction of a device that would weaken their authority in the workplace because it turned the spinner from a skilled operator into little more than a machine tender. The invention of the self-actor was directly aimed at reducing the bargaining power of these workers, something in which it was unsuccessful (Lazonick, 1979). Thus a limit was imposed on the cost saving made possible by the self-actor, slowing down its diffusion. Some idea of the magnitude of the improvements attained can be gained from Chapman's (1972) calculations of the number of hours needed to spin 100 lbs. of cotton. The "old" technology was the Indian handspinner, who took about 50,000 hours. Arkwright's rollers and the mule brought that number down to around 300 hours in the 1790s, and the self-actor reduced the figure to 135.

Although the improvements in spinning were the most spectacular, improvements in other stages of cotton production were also impressive. The cotton gin, invented by Eli Whitney in 1793, ensured the supply of cheap raw cotton to Britain's mills. A carding machine was patented by Lewis Paul in 1742 and later improved by Arkwright, who pioneered the use of large rollers to prepare the rovings for the water frame. The finished yarn was bleached using chlorine, a process invented in 1784 by the French chemist Claude L. Berthollet and improved in 1799 by Charles Tennant by combining chlorine with slaked lime to make bleaching powder. Chlorine bleaching meant a fundamental change in process, as it works through oxygenation rather than washing of the color products, and historians of the chemical industry assessed that “in the last quarter of the eighteenth century, no greater advance was made in the finishing sections of the textile trade than the art of bleaching” (Clow and Clow, 1952, p. 186). In 1783 Thomas Bell invented metal printing cylinders that printed patterns on the finished cloth. Edward Baines, one of the earliest historians of the British cotton industry, judged that Bell’s cylinder printing bore the same relation to block printing (the manual technique used until then in the calico printing industry) as throstle spinning did to the spinning wheel (Baines, 1835, p. 265). In weaving, the introduction of machines was slower. Initially improvements took place largely in the equipment used in domestic industry, which explains the long prosperity and survival of the domestic handloom weavers. The dandy loom, patented by Thomas Johnson in 1805, moved the cloth beam automatically, speeding up the weaving process with no extra effort. The first power loom was built in 1785 by Edmund Cartwright, an enterprising and idealistic clergyman, but the machine (lid not work properly until about 1815, and the finer yarns (which were more subject to breakage) were not woven by power looms until the 1830s.

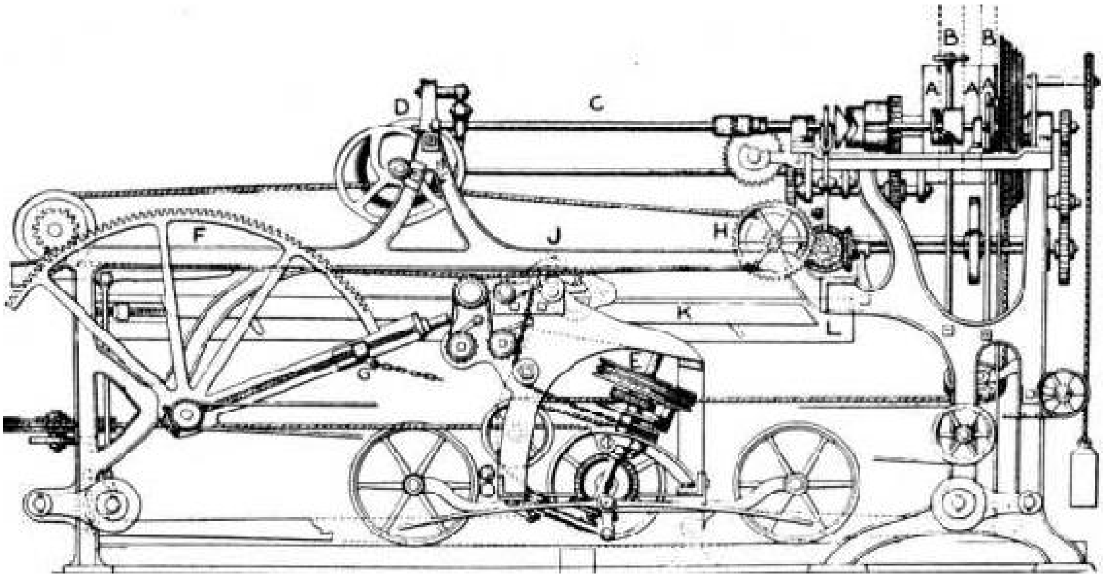

Figure 28. Side view of Richard Robert’s self-acting mule.

Sourre: W. S. Murphy. The Textile Industries Vol. 3, Fig. 130. London, Gresham, 1910. E. Norman.

“Thus, during the brief period between 1760 and 1800, a feverish wave of inventions focused on the manufacturing of’ cotton. Cotton combined qualities that are attractive to both consumers and producers: it takes dyes well, launders easily, and ventilates much better than linen and wool. Compared to its main competitors, wool and linen, cotton fibers lent themselves easily to mechanization. Moreover, the supply of the raw material was elastic. No wonder, then, that cotton grew at a rate never before witnessed in textiles, and is regarded as the quintessential growth industry of the early stages of the Industrial Revolution.

Since the sixteenth century the English woolen industry had consisted of two branches, the woolens and the worsteds. The preliminary combing of the wool in worsted production was the slowest to become mechanized. Although a number of patents were taken out on combing machines, successful combing machines were not available before 1827 and not perfected until Josue Heilmann, a Frenchman, patented his combing machine in 1845. On the other hand, Arkwright's double-roller device was well-suited to the spinning of worsted yarns. In wool the order of mechanization was reversed: preparation was mechanized before spinning. Water-driven carding machines were operating in Yorkshire in the 1770s, whereas the adaptation of the mule to the spinning of wool was not achieved satisfactorily until 1816. In weaving, power looms were applied to worsteds after 1820, but the diffusion of these machines was slower than in cotton. In wool, the yarns were too fragile for the power looms, and mechanization did not occur until the 1840s. Handloom weavers in the woolen industry survived longer than in cotton or worsteds. In the finishing processes of the woolen industry, innovation encountered some resistance, but here too mechanization proved inevitable.

Like silk, worsteds were a delicate and relatively up-market fabric woven into patterns using the so-called Jacquard loom, one of the most sophisticated technological breakthroughs of the time. The Jacquard loons was perfected in 1801 by Joseph Marie Jacquard, a Lyons silk weaver, following a century of efforts by French inventors to devise a loom that could automatically weave patterns into fabric (Usher, 1954, pp. 288-95).5 The patterns were coded on cards by means of holes representing the information in a binary code. The cards were probed by rods connected to wires, transmitting the information embedded in them. The Jacquard loom saved labor, as the draw boy was replaced by an automatic device, and it made the design of brocades much easier, permitting the weaving of more varied and richer patterns. Moreover, it eliminated the frequent and costly errors made by traditional draw looms. Despite resistance among French weavers, the jacquard loom spread rapidly in the Lyons region. A decade after its invention, 11,000 such looms were operating in France. After 1820, its diffusion in

Britain began, accelerating in the late 1830s (Rothstein, 1977).6 Apart from the Jacquard loom, the silk industry changed little. Silk throwing, once the most mechanically progressive of all textile industries, experienced no progress, and by 1825 was regarded as backward (English, 1958, p. 311).

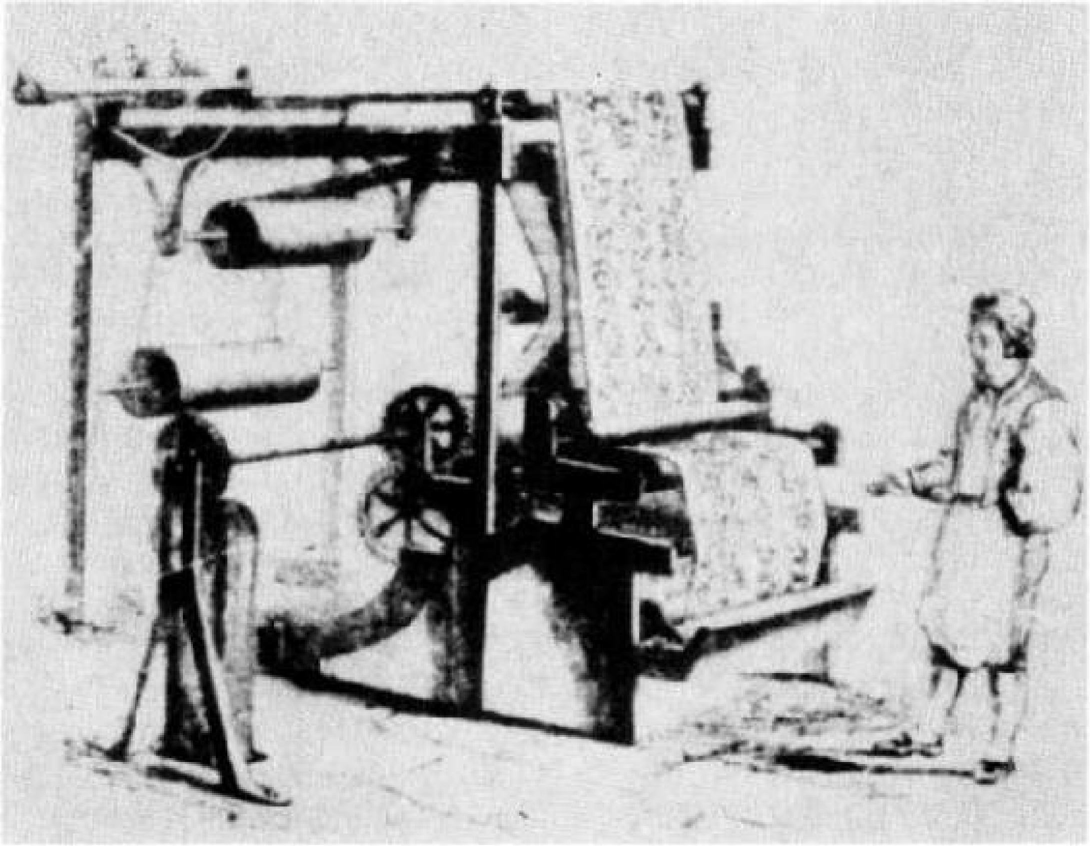

Figure 29. Cylinder printing press for the printing of calicoes, invented by Thomas Bell in 1785.

Source: Archibald Clow and Nan L. Clow, The Chemical Recoln[iOa, Batchworth Press, London.

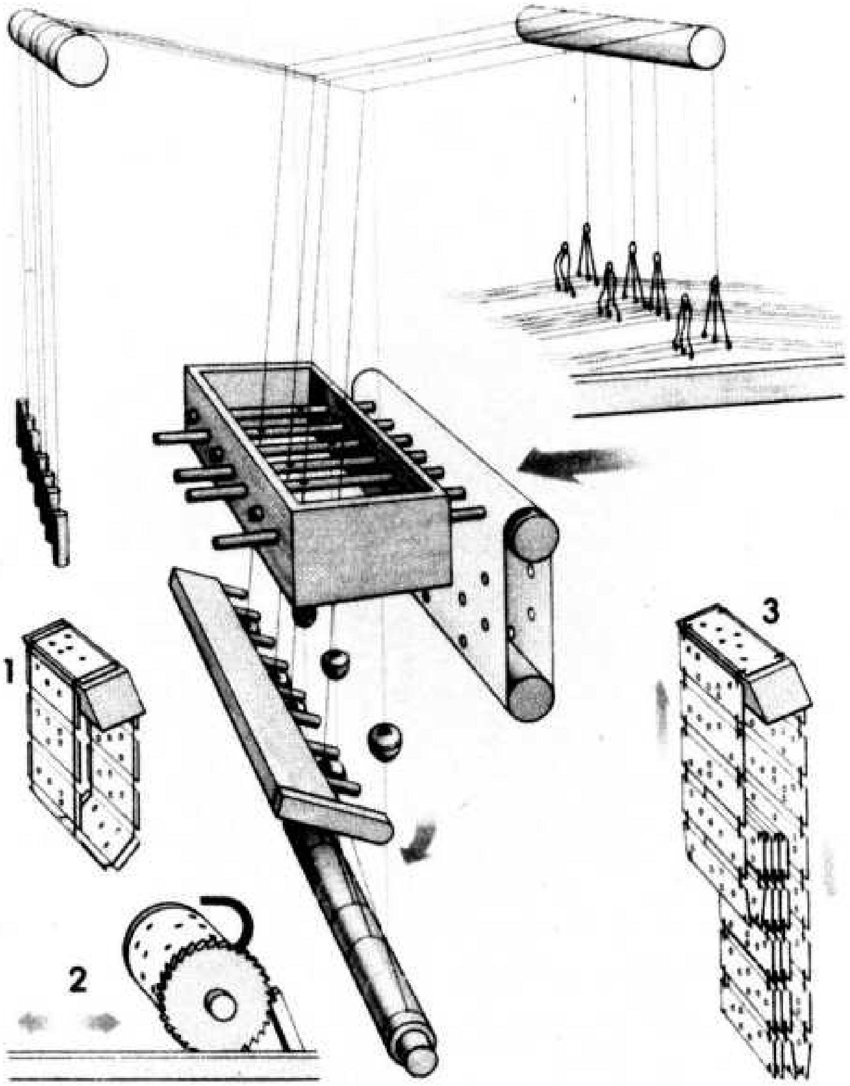

Figure 30. Stages in the development of the Jacquard Loom: (1) is the Falcon paper roll, (2) de Vaucanson’s cylinder and (3) Jacquard’s endless chain of cards. The control mechanism is shown in the center.

S nir e: Macmillan London Dd.

In the ancient and venerable linen industry, mechanization proved to be difficult. In flax, the filaments contain a rubbery substance that needs to be dissolved before spinning can take place. The search was intensified during the Napoleonic Wars, when the Continental textile industries were cut off from their sources of raw cotton supply. Napoleon, who had a keen interest in industry, offered a large financial reward to the inventor who would do for linen what Arkwright and Crompton had done for cotton. In 1810 the Frenchman Philippe de Girard perfected the idea of “wet spinning,” soaking the raw flax in a hot alkaline solution before it went to the spindles. This idea was introduced in Leeds in 1825, and the mechanization of linen spinning spread rapidly. The preparatory stages of flax processing, such as the scutching and heckling of the material (roughly corresponding to carding in wool or cotton, or combing in worsteds), which had been a highly labor-intensive cottage industry, were mechanized in the 1830s, though the finest yarns remained those heckled by hand. Moreover, the adaptation of the power loom to linen weaving was difficult because the lack of elasticity in linen caused the yarn to snap under strain. As late as 1850, there were only slightly over 1,000 power looms weaving linen in the United Kingdom, as opposed to 42,000 in wool and worsted and a quarter of a million in cotton. The technological difficulties in mechanizing the manufacture of linen cloth led to the sharp decline of this industry, with devastating effects on regions that had historically specialized in it, such as Ireland and Western Belgium.

MISCELLANEOUS TECHNOLOGICAL PROGRESS

Among the factors responsible for making the Industrial Revolution possible in the late eighteenth century rather than a century or two earlier must surely be the existence of a small but vital high-precision machine-tool making industry. In 1774, john Wilkinson patented a machine, originally designed to bore cast-iron cannon, in which the drill and material were independently manipulated. This technique greatly increased accuracy, and within two years he was hired by Boulton and Watt to finish cylinders and condensers. It is only a mild exaggeration to say that Wilkinson and his colleagues, by actually being able to manufacture the required parts as specified by the inventor, made the difference between Watt and Trevithick on the one hand and Leonardo Da Vinci on the other. Machine tools such as planing machines, milling machines, lathes, screw-cutting machines, and so on permitted the creation of precise geometric metal forms, essential to machinemaking and uniformity. It was, in the words of' one technological historian (Paulinyi, 1986, p. 277), "the most important step on the way to the production of machines by machines … it [became] possible to use iron and steel as the material whenever it appeared functional to do so."

Unlike in textiles, the masters of the engineering and machinetool industries were a closely knit group, whose members taught each other the secrets of the trade. Father-and-son dynasties, such as George and Robert Stephenson or Marc and Isambard Brunel, were complemented by master-and-apprentice dynasties. The most famous example of’ the latter was the one started by Joseph Brarnah, who had eighteen patents to his name, including an improved water closet, a wood-planing machine, sophisticated locks, and a spring-winding machine. In 1797, Bramah’s foreman, Henry Maudslay, left the firm to start out on his own, devising a screw-cutting lathe that produced screws with unprecedented accuracy and at an affordable price. He built numerous machine tools used for planing, sawing, boring, mortising, and so on (Woodbury, 1972). The famous Portsmouth blockmaking machines, devised by Maudslay together with Marc Brunel around 1801 to produce wooden gears and pulleys for the British Navy, were automatic and in their close coordination and fine division of labor, resembled a modern mass-production process in which a labor force of ten workers produced a larger output than the traditional technique that had employed more than 10 times as many (Cooper, 1984). Maudslay in his turn trained three other toolmakers-Richard Roberts, James Nasmyth, and Joseph Whitworth-all of whom made major contributions to the machine-tool industry. Nasmyth invented the steam hammer and milling and planing machines. Whitworth had no fewer than 23 exhibits at the famous Crystal Palace Exhibition of 1851 where the glories of British engineering were extolled. To his credit are, among others, a measuring machine that could measure up to one millionth of an inch and the standardization of screw threads. Richard Roberts was one of the most brilliant engineers of his time, making fundamental contributions to half a dozen inventions, including a multiple-spindle drilling machine controlled by a binary logic mechanism similar to that used in the Jacquard loom. Roberts’s improvements to Cartwright’s power loom helped transform it from a curiosum invented by a well-meaning eccentric into the backbone of’ the British cotton industry (and the (loom of Britain’s handloom weavers). His most famous inven tion was the self-actor (1830), which, as we have seen, wholly automated the mule-spinning process.

Other machine-tool makers, not all associated directly with the Bramah “dynasty,” deserve mention. In 1763 Jesse Ramsden built a dividing machine for the accurate graduation of circles, crucial to the construction of navigational and surveying instruments. Matthew Murray and Bryan Donkin also contributed to the design of improved machine tools. William Fairbairn, a producer of improved waterwheels, steamboats, and boilers, was a worthy heir to John Smeaton. In the United States, Eli Whitney, John Hall, Simeon North, Thomas Blanchard, and others pioneered new machine tools, paving the way eventually for the American System of interchangeable parts.

In the ceramics industries, the location and timing of technological change were quite different than in textiles and metallurgy. Here the Continent played a major role, and many important technical developments occurred before 1750. In the seventeenth century Dutch craftsmen, struggling to imitate Chinese blue and white porcelain, hit upon the processes of making the tin-and-enamel wares for which Delft is famous. Porcelain was produced successfully in 1708 by J. F. Bottger, who was employed by August the Strong, Prince-Elector of Saxony. Dresden chinaware was made in Meissen, using a technique that was kept secret by the Saxons. It took the rest of the Continent several decades before they were able to copy the process. England came up with a close substitute in the salt-glazed earthenwares produced by John Astbury of Staffordshire in about 1720. By 1759, when the renowned Josiah Wedgwood started his factory in Bur- slem, he could draw upon a venerable tradition of making an excellent product. In the preceding century, the British pottery industry had adopted coal as it fuel for most purposes, as well as new raw materials, such as ball clay and flint. Wedgwood is justly famous for his rationalization of production employing steam engines, his use of a fine division of labor, and his ability to market a relatively inexpensive product to snobbish consumers, competing successfully with the more expensive hard-paste porcelains made on the Continent. Wedgwood was, however, also an important inventor, who pioneered the use of gold and platinum as glazes on lustre wares, and whose work on pyrometers earned him a fellowship in the Royal Society (1783).

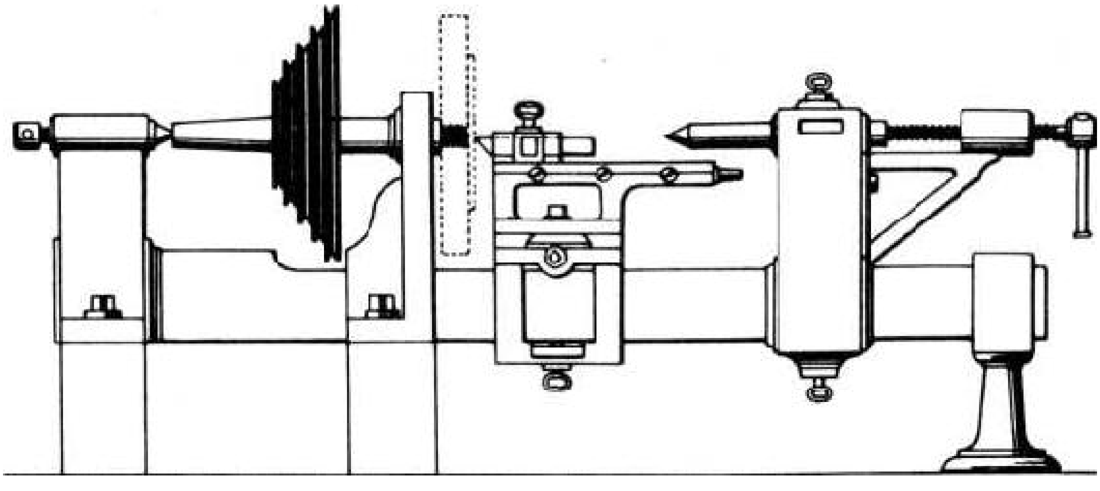

Figure 31. Henry Maudslay’s slide and finishing lathe, dating from 1800. Source: Maurice Daurnas, A History of Technology and Invention, Vol. III, Crown Publishers Inc., New York.

In the glass industry, too, Britain followed the Continent. In or around 1688, French glassblowers adopted the cast-plate process, which produced flat glass (by far the most important output of the industry) with a much more even and flat surface than the cheaper method of* blown “crown” glass. The great royal manufacture at St. Gobain led in the production of window glass and mirrors using this system. Its adoption in Britain dates from only the 1770s, and even then it remained dependent on French know-how. On the other hand, the British pioneered glassmaking using a coal-fired reverberatory furnace. Through covered crucibles, the smoke was prevented from discoloring the glass, it technique the French (lid not master until the Revolution (Scoville, 1950, p. 43). The most important breakthrough in the glass industry was made in 1798 by Pierre Louis Guinand, a Swiss, who invented the stirring process in which he stirred the molten glass in the crucible using a hollow cylinder of burnt fireclay, dispersing the air bubbles in the glass more evenly. The technique produced optical glass of unprecedented quality. Guinand kept his process secret, but his son sold the technique to it French Manufacturer in 1827, who in turn sold it to the Chance Brothers Class Company in Birmingham, which soon became one of’ the premier glassmakers in Europe.

In the technology of papermaking, machinery producing continuous sheets had been patented in 1798 by the Frenchman Nicholas Louis Robert. Robert’s main idea was to produce the paper on an endless belt of woven wire, replacing the process that produced separate sheets made in molds used until then. The principles developed in Robert’s machine were further developed by the British engineer Bryan Donkin and eventually came to he known as the Fourdrinier machine, after a London stationer who was the first to adopt the new machinery successfully (Coleman, 1958, pp. 179-90; Clapham, 1957, p. 416). Although the paper industry is not often thought of as a typical industry of the Industrial Revolution, the Foudrinier machine was in fact it revolutionary device. It reduced the time involved in making it given piece of paper from three weeks to three minutes, and five workmen in it mill could furnish enough work to keep 3,000 workers busy. Chlorine bleaching, crucial to the development of the cotton industry, was also applied successfully to paper pulp from the 1790s on, thus permitting the use of dyed and printed rags in the production of paper.

Britain, then, had no monopoly on invention, but when it was behind, it shamelessly borrowed, imitated, and stole other nations’ technological knowledge. Another good example of Britons applying new technology developed elsewhere was the chemical industry. Beithollet, the inventor of chlorine bleaching, was French, as was Nicholas Leblanc, who developed the soda making process named after him. Leblanc reacted salt and sulphuric acid to produce Sodium sulphate, which after heating with lime or charcoal yielded raw soda together with hydrochloric acid, it noxious by-product. The Leblanc process became the basis of the modern chemical industry and is regarded as one of' the most important inventions of the time.' In the adoption of' soda, Britain was relatively slow, and only in the 1820s did it start to adopt Leblanc's process on it large scale. The explanation usually given for this delay is the high tax on salt., which made artificial soda more expensive than vegetable alkali. Once the salt tax was repealed, British soda production grew rapidly and by the 1850s exceeded French output by a factor of three (Haber, 1958, pp. 10-14). In other areas of the chemical industry, however, Britain led the Continent from the middle of the eighteenth century. Sulphuric acid, known as vitriol, used in bleaching and metallurgy, was obtained by adding saltpeter to sulphur in large glass vessels, a process invented in France in 1666. The French were tenable to make much use of this invention, and in about 1740 the process was adopted by Joshua Ward, an English pharmacist who adopted the glasschamber process, and the price of sulphuric acid fell from almost £9 to 10 s. per pound. In 17.46, john Roebuck perfected his lead-chamber process for the production of sulphuric acid, and Britain remained the center of this industry. Only after the middle of the nineteenth century did the Germans establish firm leadership in chemistry, thanks to their superior chemists.

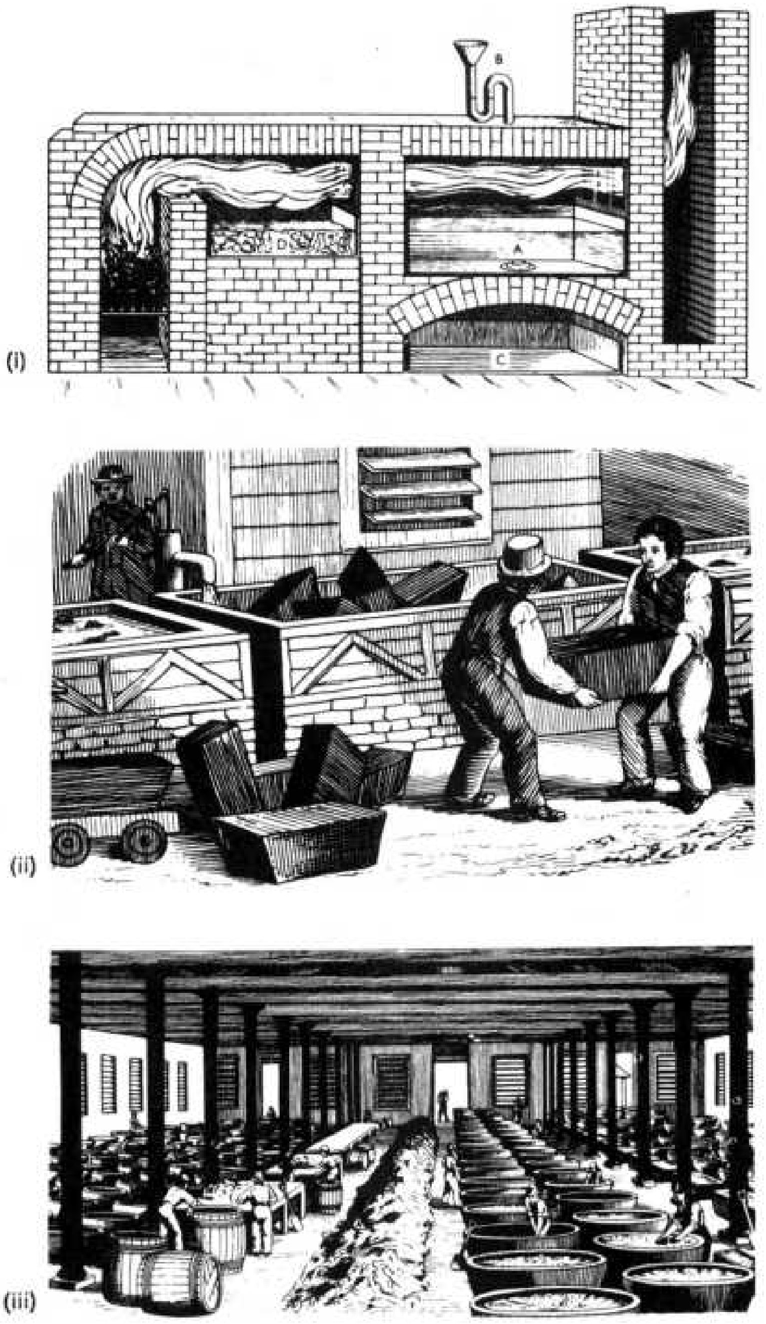

Figure 32. Soda manufacture using Leblanc’s process: (i) shows the furnace in which the reaction takes place; (ii) shows the big vats in which the soda was dissolved out; (iii) shows the preparation of soda for the glass industry.

Source: (i) After C. Tomlinson. Do’ Useful Arts and Manufactwes of Grrat Britain, Part 11, Section: ”I-he Manufacture of Soda,” p. 33. London, 1848. E. Norman. (ii, iii) After C. Tomlinson. Ibid., p. 26. 1). E. Woodall.

An interesting example of international collaboration in technological progress was the development of gaslighting. Although this invention was probably modest in its contribution to national income, it was important in its effect on the quality of life: gaslit streets were safer, gaslit homes promoted literacy, gaslit theatres made entertainment more sophisticated, and gaslit factories made night work cheaper and more efficient. Prior to 1780, lighting technology had changed little since antiquity. Lamps burning rapeseed and similar oils provided a smoky light. Candles were mostly made of tallow and produced a smoky and malodorous flame. Wax candles were superior, but too expensive to be used widely.

Gaslighting was a joint German-Anglo-French project. The use of gas as a source of light was first pointed out by the Belgian physicist Jean Pierre Minkelers and the German pharmacist. G. Mickel in the late I 780s. In 1799, the Frenchman Philippe Lebou combined a woodderived gas with the Argand burner, developed by the Frenchman Aitne Argand in the early 1780s.” In Lebon’s so-called thermolamp, the gas and the air were introduced separately, and the heavier byproducts were collected in a special receptacle. In 1798, the Scotsman William Murdock, who worked for Boulton & Watt (which had bought Argand’s patent in Britain), lit his forge with gas derived from coal, which soon proved superior to gas oracle from wood. By 1807, Manchester’s cotton mills and London’s Pall Mall were illuminated by gas. ‘fhe Englishman Samuel Clegg showed how gas could be distributed from it central production site to individual consumers using hydraulic gas mains. His son-in-law, John Malam, developed in 1819 it metering system that could monitor the quantities used by each customer. Following the return of peace in 1815, the idea spread rapidly through the Continent: the work of a German chemist appropriately named Wilhelm Lampadius led to the illumination of Berlin streets in 1826. Further innovations, such as filtering the gas through quicklime to remove the noisome odor caused by sulphurite hych’ogen, helped to reduce the price and improve the quality of gaslighting.

In mining, the years of the Industrial Revolution were marked by gradual progress but few spectacular advances. Coal became of overgrowing importance to the economy, in part because of its use in engines and metallurgy, and in part because a growing and more prosperous population demanded it for home heating. Yet aside from the use of steam engines in pumping water from the mines, the only radical invention in coal mining was the safety lamp, invented by Humphrey Davy in 1815. Better ventilation, the introduction of rails in underground hauling, and the redesign of* shafts for increased safety were the main foci of progress in mining. By 1830 steamdriven fans came into use, further reducing the dangers of’ explosion. The technical problems involved in using power machinery inside it mine could not be solved, however. The increase in production here consisted primarily of a shift along the supply curve, rather than an outward movement of the curve, as was the case in textiles and metal. In other words, output in the mining sector increased primarily because more resources were allocated to it, not because new techniques allowed existing resources to produce cheaper or better.

Finally, one of the greatest macroinventions of all times occurred during the heyday of the Industrial Revolution, yet it is rarely mentioned in connection with it. The invention of ballooning by the Montgolfier brothers in France in 1783 is surely an epochal invention in terms of novelty and originality. Since time immemorial people had dreamed of human flight, but, some ill-fated attempts aside, it had never been achieved. Attempts to fly typically sought to imitate birds, equipping the flyer with wings and a tail, but without the faintest understanding of’ the principles of’ aeronautics. Joseph de Montgolfier was the first to take an entirely different tack, that proved amazingly successful. Montgolfier was aware of’ Henry Cavendish’s discovery in 1766 of’ hydrogen, it gas lighter than air. He believed that fire gave off a similar gas, and that when the gas was captured in a closed vessel, that vessel would be lighter than air and thus rise. The reasoning was thus partly fallacious. What made the Montgolfier balloon rise was not a gas lighter than air but air itself, which, heated, expanded and thus reduced its specific weight. Success was immediate. Half a year after the emergence of the idea, the famous demonstration in Annonay took place. On November 21, 1783, the first two human beings lifted off, traveling through the air and living to tell about it. Except for it few military applications, ballooning was, of’ course, of limited direct economic effect. But there can be little doubt that the consequences of’ the invention of ballooning were far-reaching. Few inventions were more powerful in accustoming people to the idea of technological progress and alerting them to the ability of human ingenuity and creativity to control the forces of nature and do things never clone before.

The technological developments in the British manufacturing sector increased output by hitherto unimagined factors. The price of cotton cloth declined by 85 percent between 1780 and 1850. As elementary economic analysis shows, in a competitive economy technological progress in existing goods is usually transmitted to consumers through lower prices. The role of demand in the process was largely passive, as consumers responded to lower prices by buying more or, in the terms of economics, slid down their demand curves.” Technological progress created both totally new goods and higher-quality old goods. The shift in supply thus either satisfied an already existing demand or created new needs previously not explicitly felt. Either way, it makes little sense to try to explain the timing or the location of the Industrial Revolution by exogenous changes in consumer demand for goods and services.

Why did these breakthroughs not occur earlier? Although the innovations that made the Industrial Revolution typically did not depend on new scientific knowledge, the fact remains that the technical problems that the engineers of the Industrial Revolution solved in metallurgy, power technology, and textiles were difficult. Given the tools, materials, and resources at the disposal of the most talented men in Europe, it is not surprising that it took it long time to tackle many of the challenges. Those who claim with Hobsbawnt (1968, p. 38) that there was nothing inherent in the new technology of the Industrial Revolution that could not have developed 150 years earlier confuse scientific knowledge with technological ability. Easy as they may seem to its today, the problems were often simply hard. Even when all that was required was to combine previously known pieces of’ technical know-how into it new gadget that would actually work, the effort required by the inventor was often considerable. The “invention” and “development” stages of technological progress were not yet distinct. In recent years there has been it tendency to downgrade the role of key persons in economic history, and to tell the tale of’ the Industrial Revolution in terms of inexorable social forces. This approach was largely it reaction to the earlier simpleminded heroic tales of invention, in which it handful of brilliant individuals were credited with all technological progress. But it is possible to go too far in the other direction. The changes in the British economy during the Industrial Revolution were no doubt the result of profound economic, social, and demographic forces. But inge nious, practical, mechanically minded people came up with the ideas that changed the world. Ideas by themselves were not good enough, as a long line of frustrated inventors found out. Dexterity and perseverance were equally important. Samuel Crompton, the yeomaninventor, wrote that he spent “four-and-a-half years at least wherein every moment of time and power of mind as well as expense which my other employment would permit were devoted to this one end” (cited by Baines, 1835, p. 199). Watt first conceived of his separate condenser in 1765; the first commercially successful machine began to operate only in 1776. The invention of the self-actor by Roberts involved a concentrated research effort (stimulated by the spinners' strike of 1824) that cost ,£12,000 and six years of hard work to complete. In addition to everything else, invention required people of unusual ability, such as Watt, Smeaton, Trevithick, and Roberts, as well as people of unusual energy, daring, and luck, such as Arkwright and Boulton. The supply of talent is surely not completely exogenous; it responds to incentives and attitudes. The question that must be confronted is why in some societies talent is unleashed upon technical problems that eventually change the entire productive economy, whereas in others this kind of talent is either repressed or directed elsewhere.

The story of the Industrial Revolution is, of course, far more than the tale of ‘a handful of major inventors. The names mentioned above are but a small fraction of those who contributed to the new technology. Right below the "superstars" were hundreds and thousands of engineers, technicians, entrepreneurs, foremen, and gifted amateurs who made less spectacular contributions to technological progress. By adapting, modifying, improving, debugging, and extending earlier inventions, they were indispensable to the success of the uncoordinated, unconsciously joint project called the Industrial Revolution. In addition, we should not forget that there were even more numerous and more anonymous tinkerers and inventors who made things that did not work, or who were scooped by earlier or luckier competitors.