INDUSTRIAL REVOLUTION. The term *Industrial Revolution* is normally reserved for a set of events that took place in Britain roughly from 1760 to 1830. The historical events in question consisted of a set of technological, economic, and social changes that in the long run revolutionized not just the British economy but that of the rest of western Europe, North America, and eventually much of the rest of the world. The Industrial Revolution brought about a "modern" economy in which technological progress did not just happen from time to time in isolated sectors but became a sustained and continuous process, resulting eventually in unprecedented economic growth and increases in living standards in much of the world. Its effects led to a complete reorganization of production, consumption, locational patterns, international relations, demographic behavior, and almost every aspect of the human condition. Yet unlike the American and French revolutions that were contemporaneous with it, the Industrial Revolution brought economic changes that were neither dramatic nor very abrupt. There are no industrial equivalents to the Battle of Lexington or the conquest of the Bastille. Yet in the economic history of humankind, the Industrial Revolution marks a watershed. Although some other events are sometimes designed as "industrial revolutions," to say nothing of "agricultural," "demographic," and other assorted revolutions, none of them equals the Industrial Revolution in importance.

The Industrial Revolution was not the beginning of "industrialization"; much manufacturing had already been taking place in European cities and in the countryside by the middle of the eighteenth century. Nor did the Industrial Revolution increase by much the number of human hours spent on manufacturing processes; industrial output expanded greatly, but in the long run productivity increased so much that labor could be siphoned off into services. Nor was the Industrial Revolution the beginning of innovation as a force for change in the human condition; early medieval and renaissance Europe had witnessed a series of inventions that revolutionized agriculture, textiles, power use, shipping, iron making, communications, and warfare. Nor was the Industrial Revolution the absolute beginning of economic growth as such; the British economy in 1700 was clearly much richer than it had been at any point in its past, as Adam Smith had already noted. The Industrial Revolution was in some sense a change in the *degree* of change—but in economic history degree and amount are everything.

It should be emphasized nonetheless that the classic Industrial Revolution was a localized affair, one that most Britons were only dimly growing aware of. Napoleon famously referred to Britain as a nation of "shopkeepers," not "cotton spinners." Many of the most interesting developments took place in two or three loci; a number of counties around Lancashire and the town of Manchester, the Scottish Lowlands, and some smaller regions in the midlands and Wales saw almost all of the action. In the eastern parts of the country and the area south of London, there was little evidence of rapid economic change before 1830. After 1830, the structural change in the economy accelerated rather than wound down, thanks to the railroads, the telegraph, and the spreading of technological changes to new industries. The foundations of a new economy in which change was the normal condition were laid from 1760 to 1830.

Technology was at the core of everything. An anonymous schoolboy, immortalized in a classic 1948 book by T. S. Ashton, called the Industrial Revolution "a wave of gadgets" that swept Britain. Yet these inventions did not rain upon Britain like manna from heaven. Technology may have been an engine that propelled the economy forward, but it took its fuel from a society and an economy that were exceptional, not just relative to non-European nations but even in comparison to its close European competitors and enemies such as France and the United Provinces. Eighteenth-century Britain was what we may call a technologically competent society. It was teeming with engineers, mechanics, millwrights, and dexterous and imaginative tinkerers who spent their time and energy designing better pumps, pulleys, and pendulums. Even wealthy landowners and merchants displayed a fascination with technical matters. Men such as John Smeaton, often called the first modern engineer, Joseph Bramah, thought of as the originator of hydraulic power, and the prodigiously gifted engineer Richard Roberts could turn to almost any technical question and resolve it as well as could be done. Britain had an unusual number of such people. One famous quote from a Swiss visitor in Britain in 1766 declared that for a thing to be perfect it had to be invented in France and worked out in England. As it turned out, some of the great inventions of the Industrial Revolution were produced in Britain, whereas others came from the Continent. Yet in the kind of society that Britain was in these years the question of "where it came from" was not important. "Does it work?" and "Can it make money?" were what mattered.

The main technological breakthroughs of the Industrial Revolution were the famous ones listed in high school history textbooks; yet these "heroic" inventions were only the tip of the iceberg. Right below them lay a large number of important breakthroughs that solved major bottlenecks and opened the door to further improvements. A third layer contained an even larger number of small improvements, adjustments, new applications, and minor technical insights that never made it to the patent office, much less to the history of technology books; yet they, maybe more than the textbook inventions, consolidated the

achievements of ingenuity and imagination in terms of productivity gains.

The most famous invention of the Industrial Revolution was the steam engine. Strictly speaking, the steam engine was the result of work carried out, mostly on the Continent, in the last third of the seventeenth century. The first steam engine prototype was built by a Frenchman named Denis Papin, but there is no question that the first useful atmospheric steam engine was built in 1712 by a Cornish mechanic named Thomas Newcomen. For half a century Britain used Newcomen engines, which, though noisy and voracious in their fuel use, served mostly as pumps. The conversion of the steam engine into a source of industrial power was the handiwork of Scottish inventor James Watt, who introduced a number of famous improvements to the steam engine, such as a separate condenser, the principle of double-acting expansion, improved gears, and regulators. Watt turned steam power from an atmospheric pump to a true steam engine. When his patent expired in 1800 after thirty-one years, a new principle in steam power, the high-pressure engine, was developed, which soon threatened the Watt engine's monopoly. High-pressure engines provided increased power from engines lighter and smaller than older counterparts, and were thus ideal for transportation; and after years of experimentation they were successfully adapted to locomotives by Robert and George Stephenson, in 1825.

Yet the steam engine, its psychological impact and technological future aside, had a relatively minor impact on the British economy before the advent of the railroad. Of about twenty-two hundred machines operating in Britain in 1800, almost half were employed in mining and quarrying, and about 40 percent in manufacturing. By 1835 Lancashire had switched over to steam, but the cotton industry in the rest of Britain still depended on water mills for about half its horsepower. The Industrial Revolution witnessed enormous progress in the utilization of waterpower, above all Smeaton's breast wheel (which combined the advantages of over- and undershot wheels), and the growing use of iron in the manufacturing of water wheels. Even more than did steam, waterpower benefited from the growing scientific understanding of its principles, especially among hydraulic engineers in France. In other nations, especially the United States, France, and Switzerland, waterpower remained of central importance.

A second industry often identified with the most dynamic aspects of the technology of this time is textiles. By the middle of the eighteenth century, cotton was a small and rather unimportant sideshow in the British textile industry, famous for its woolens. Cotton's growth during the Industrial Revolution was truly amazing. Value added in cotton went from less than half a million pounds in 1760 to around 25 million in the mid-1820s. It is no wonder that some economic historians have thought of this industry as the "leading sector" in the Industrial Revolution. The reason for this success was cotton's physical characteristics. It lent itself uniquely to mechanization and mass production and produced a good that was of even quality, attractive, and above all inexpensive.

The weaving of cotton had already gained in productivity when the flying shuttle was introduced in the 1730s and 1740s, but spinning in 1760 was still carried out by hand. As long as spinning remained a manual process, the yarn produced remained both costly and of uneven quality. This bottleneck was resolved by a string of brilliant mechanical inventions between 1765 and 1779, which led to the famous mule (so-named because it consisted of a combination of the 1765 spinning jenny and the throstle), patented in 1769. The mule became the industrial machine par excellence, and within a few years it was coupled to the steam engine, so that the first truly "modern" factory (or "mill" as it was known at the time) was born. The mule was perfected in 1825 by making it automatic through the introduction of the self-actor. An indication of the magnitude of the improvements attained is shown by the number of hours needed to spin a hundred pounds of cotton. The "old" technology employed an Indian handspinner, who took about 50,000 hours. The mule brought that number down to around 300 hours in the 1790s, and three decades later the self-actor reduced the figure to 135.

Many of the other processes used in manufacturing cotton were also mechanized to some extent, though some of the problems proved more difficult than others. Carding, the process that prepared the cotton for spinning, was mechanized early on; ginning, the removal of the seeds from the raw cotton, was mechanized in 1793. Weaving by machine turned out to be more difficult, and power looms did not become successful until after 1820, though their use then spread rapidly. Calico printing was mechanized by the invention of copper rollers that printed patterns on finished cloth. Bleaching was revolutionized by the introduction of chlorine-based bleaching agents in the 1790s. By 1830 only the extremes of the upstream and the downstream of the industry were not mechanized: raw cotton was still grown and picked by hand in American fields, largely by black slaves; and finished clothes were still sewn together by hand by apparel makers, seamstresses, and tailors.

Growth in the mechanization of textiles was not confined to cotton, but the other textiles inevitably lost a great deal of market share. Worsted (combed wool) yarns were easily adapted to the cotton spinning machinery, but the combing process itself was not mechanized successfully until the middle of the nineteenth century. In the heavy woolen industry, the labor-intensive preparation and finishing processes were successfully mechanized early on, but spinning and weaving proved more difficult and were not fully mechanized until the 1840s. Linen, the other

major textile, made from the stem of flax, was also hard to spin mechanically. A French inventor, Philippe De Girard, tempted by a large prize promised by the Emperor Napoleon, solved the problem in about 1810; and his "wet spinning" process was introduced into the flax-spinning industry in Britain in about 1825. One of the most interesting inventions of the Industrial Revolution was the loom invented by Joseph-Marie Jacquard in 1801, which automated the weaving of patterns in a piece of fabric. Used for upmarket silks and worsteds, this machine was the first to code information using a binary code; and it inspired the work of Charles Babbage, a British mathematician who pioneered the first digital calculating machine.

A third area in which the Industrial Revolution achieved major advances was iron making. One important innovation was the use of new fuels in the smelting of iron ore in blast furnaces. The replacement of charcoal by coke (purified coal) in blast furnaces remedied the costly need to access remote forest areas. Blast furnaces became bigger, hotter, and more efficient as more powerful machinery was used to blow air into the furnaces. In 1828 a Scotsman, James Neilson, discovered that by using the blast furnaces' own gases he could cut fuel usage by up to a factor of three.

The problem remained, however, to refine the end product of the blast furnace, known as pig iron, into the more malleable and usable wrought iron. After decades of experimentation and searching, a British ironmaster named Henry Cort solved the problem in 1785, through what became known as the puddling and rolling process, a truly epochal breakthrough of the Industrial Revolution. Cort's process took Britain (and soon after that, the rest of Europe) by storm. In one dramatic stroke, the bottleneck that had occupied thousands of small-time forges and smithies was resolved. Even in steelmaking, a difficult art in which specialists fiercely kept their trade secret, there was progress: Benjamin Huntsman, a Sheffield steelmaker, perfected what became known as crucible steel, a high-quality product that became famous the world over. Steel remained expensive, however, and would not be mass-produced until the second half of the nineteenth century.

These three sectors—energy, textiles, and iron—are rightly famous for their bold and pathbreaking innovations. Yet the period witnessed a large number of other industries that in some way or another modernized, either by revolutionizing the manufacturing process itself or by adopting some form of machinery. In chemicals, two major inventions stood out. The first was the manufacturing of alkalis (used in industries such as soap-boiling and glassmaking) by means of a soda-making process perfected by Nicholas LeBlanc in 1787. This process dominated world production until the 1860s. Even more revolutionary was the second invention, the use of a new chemical (discovered only in 1774), chlorine, for the bleaching of textiles. Long, expensive processes of bleaching were replaced, almost overnight, by a fast and reliable alternative.

Machine and instrument making also made enormous progress. John Wilkinson, a Shropshire ironmaster, patented a boring machine to be used for cannon, which he adapted to make the cylinders needed for Watt's engines. One of the most famous technological challenges in the Western world, how to measure longitude at sea, was solved by a British clock maker, John Harrison, around 1762; although it still took a few decades for such clocks to be made cheaply, the invention stands as further testimony to British ingenuity in these years. A long list of British engineers and instrument makers, including Joseph Bramah, his brilliant student Henry Maudslay, and Maudslay's gifted student Richard Roberts, redesigned every machine-making tool known; lathes, planing machines, boring machines, screw-cutting machines, and measuring tools, all looked very different in 1820 compared to 1760. These tools made it possible to build parts and machines with greater and greater accuracy and thus increased industrial efficiency.

Many of the "old" industries also were overhauled. In papermaking, a machine that produced paper in a continuous roll rather than by individual sheet, patented by a Frenchman named Nicholas Louis Robert, was introduced around 1800. In glassmaking, pottery, flour milling, sugar refining, printing, and mining, the use of machines, whether steam-driven or not, changed the way production took place. The invention of gaslighting in the 1790s not only helped to light streets but allowed factories to work longer hours in the short winter days of northern Europe. Roadbuilding was revolutionized by John McAdam, canal building by James Brindley, and bridge construction by Thomas Telford. The iron bridge, the first of which was completed in 1779, became a symbol of the Industrial Revolution. Even before the electromagnetic telegraph, long-distance communication made a giant step forward with the introduction of the semaphore telegraph. Food canning, invented in 1795, was picked up quickly; and in 1814 the British navy and army were already being supplied with canned soups and meats. Many small but useful inventions that came into being in those years simplified daily life: matches, steel pens, lawnmowers, safety lamps for miners. Innovation was simply in the air: in 1783 for the first time in history humans flew, if only in hot air balloons; in 1796 Edward Jenner vaccinated people against smallpox. In short, the years of the Industrial Revolution were truly years of miracles.

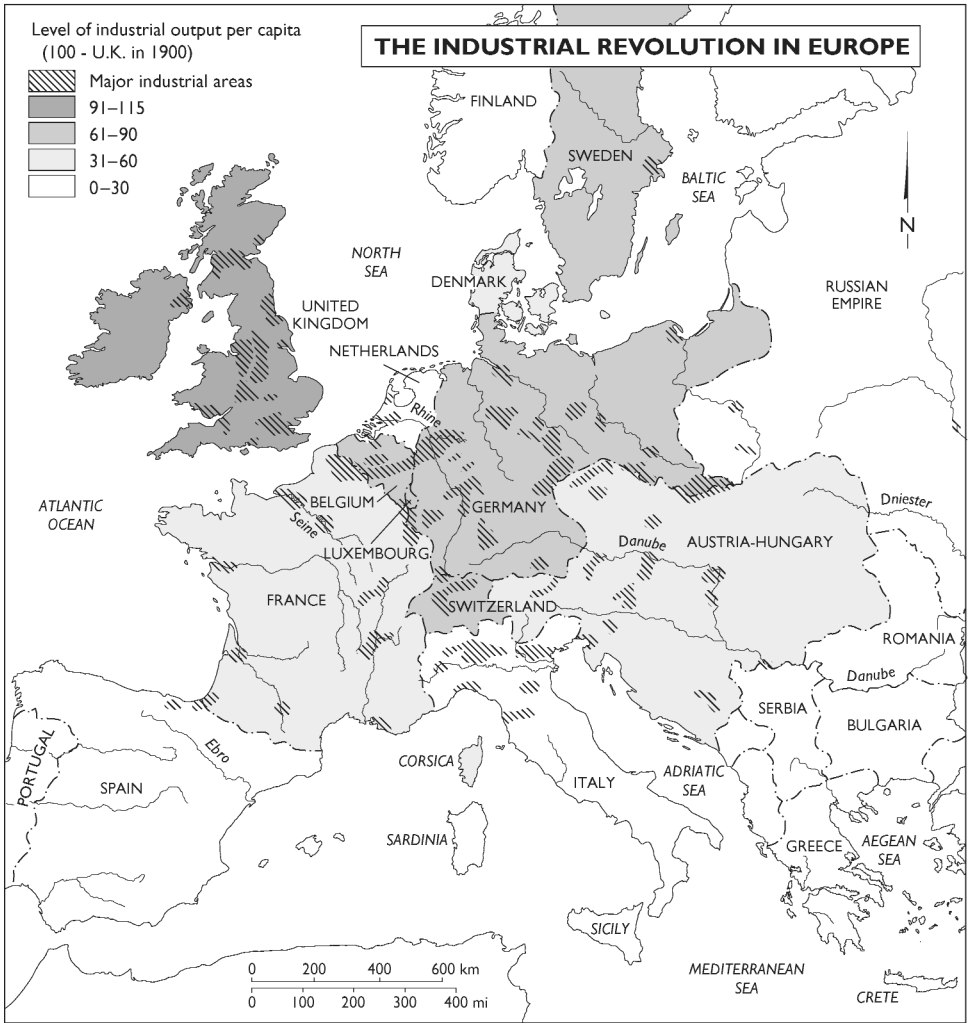
The economywide effects of the Industrial Revolution were less than spectacular, however. Estimates about growth of income per capita for the years from 1760 to 1800 put it at 0.2 percent a year, and for the period from 1800 to 1830 at the modest level of 0.5 percent. These

INDUSTRIAL REVOLUTION. The iron bridge at Ironbridge, Shropshire, England, circa 1900. (Prints and Photographs Division, Library of Congress)

modest numbers have persuaded some authors that perhaps the entire concept of Industrial Revolution is misplaced. Clearly, one should not identify the Industrial Revolution with the entire British economy for this period. The dimensions of the "modern" sector—those industries and services in which technological progress was the most marked—were quite modest in the early stages; although this sector was growing rapidly, its impact on the economy at large was limited. For the hundreds of thousands of workers employed in agriculture, construction, shipbuilding, retail trade, personal services, and other traditional occupations, the new technology as yet made little or no difference. Furthermore, the Industrial Revolution was a period of rapidly growing population, and the economy had to feed, cloth, and shelter ever-increasing numbers of people. To make things worse, Britain fought a number of expensive wars (the American independence war and the French wars) between 1756 and 1815, with only two decades of peace in between. Wars raised taxes and, because of trade disruptions, the prices of consumer goods. It is no wonder that real wages and average living standards show little trend upward until the 1840s. Those who lived through the Industrial Revolution did not enjoy its fruits.

In the process of structural transformation of the industries, a great deal of human suffering was experienced along with the obvious gains to consumers. The new technology produced cheaper and better goods that competed with those produced by home-workers, who gradually lost their desperate struggle with the machines. The plight of the handloom weaver who was gradually pushed aside by the power loom after 1815 is well known, but in many other areas in textiles and handicraft production the Industrial Revolution also meant the end of independent producers and their way of life. Moreover, work in the early factories was very difficult. Work hours were long, and the shop floors were noisy, cold, and often dangerous. The workers—many of them women and teenagers—had to submit to the discipline and regime of the factory, controlled by strangers, in which transgressions were severely penalized. The industrial novels describing the harshness of this life made a deep impression on contemporary readers, but it took a long time for effective measures to restrain child labor and factory conditions to be enforced.

To make things worse, the Industrial Revolution was accompanied by rapid urbanization. The industrial towns, such as Manchester and Glasgow, grew at unprecedented rates, attracting thousands of rural workers or their family members. Yet life in the early industrial towns was very unpleasant. The overhead capital in cities—devoted to water supply, sewage and garbage disposal—could not accommodate the sudden surge in the number of inhabitants. People lived in overcrowded, dirty, ugly, dark tenements, and poor sanitary conditions led to high mortality rates. These conditions inspired an angry literature, of



which Friedrich Engels's *Condition of the Working Class in England* (1844) is the most celebrated contribution. Part of the higher wages earned by factory workers thus must be regarded as compensation for deterioration in their quality of life relative to village conditions.

Life was not easy even for the industrialists and entrepreneurs who were the driving force behind the innovation process. For every successful capitalist such as Richard Arkwright or Boulton, there were many who failed for one reason or another. Britain's legal framework was not friendly to limited-liability corporations, and many bankruptcies ensued because of complex networks of partnerships with unlimited liability. Henry Cort, for one, lost all his business because of such a partner and in the end had to be satisfied with a modest pension while others used his invention. Dr. John Roebuck, Watt's first partner, also went bankrupt, because of the troubles of one of his other partners. On the surface patent law meant protection for inventors, but with some notable exceptions it actually provided few financial safeguards. Richard Arkwright, the cotton spinner, just gave up his patent altogether rather than continue to spend time and money on litigation. Then, as now, entrepreneurial activity was a highly risky gamble, with the odds stacked against bold innovators. The historical record, by recounting the success stories, tends to obscure these risks. The people who became rich and richer during the Industrial Revolution were those who owned land, particularly urban real estate and lots with favorable physical characteristics such as mining or waterpower sites. Also merchants, shipowners, and the providers of financial services to trade generally did well. Moreover, many of the successful industrialists came from the ranks of the mercantile and landowning classes. The Industrial Revolution created a class of rich capitalists, but

not all of the newly rich were industrialists and certainly not all industrialists became rich.

The most remarkable social consequence of the Industrial Revolution was the emergence of the factory. It is insufficiently realized today that before the Industrial Revolution the vast majority of people worked in their homes or in fields or attached workshops. Even workers who had lost their economic independence, such as those in the so-called putting-out industries (in which a merchant supplied them with raw materials or intermediate products that the worker then processed at a fixed piece wage), worked in their own homes. Independent artisans, shopkeepers, and farmers were domestically based, and employed members of their own households. Even those whose work required being away from home, such as masons and carters, normally operated from a home base. Colliers, soldiers and sailors, and some workers in manufacturing (in large ironworks, breweries, and shipyards) were among the few who worked under conditions that would remind one of modern labor arrangements. With the Industrial Revolution, this situation began to change. The "mill," in which production took place in a large room in coordinated fashion and under supervision, slowly spread; and although the changeover took many years to reach its full course, its roots are clearly in the fateful years of the late eighteenth century.

Karl Marx, one of the first social commentators to fully realize this, found the rise of the factory to be a deplorable development. Workers were "alienated" from the means of production, treated as machines, exploited, and often humiliated. Modern research is a bit more cautious: conditions in the mills were harsh, but the domestic manufacturing system was not less backbreaking, and the harsh discipline of factories has to be compared with the discipline to which apprentices, wives, and children were subjected in the traditional economy. In the nineteenth century, those domestic industries that remained were known significantly as "sweated trades." At first, factory masters preferred the more docile and malleable labor supplied by women and youngsters and found it difficult to manage adult males, who were often unruly and intoxicated. Over time, however, many factory owners came to realize that factory labor required male workers as well and did their best to convince these workers, by a mixture of propaganda and incentives, to conform to factory requirements of punctuality and obedience.

The new factories required more than just buildings, machinery, and lighting. With the emergence of large production units, new management problems surfaced. Some of the most successful entrepreneurs—such as Robert Owen, the cotton spinner, and Josiah Wedgwood, the pottery manufacturer—were able to overcome lack of experience and training through intuition and genius, and put together well-organized operations. But in this age most managers had little experience in cost and capital accounting, inventory control, personnel management, financial organization, and marketing. All of those functions had to be improvised and mastered through experience. A few did well, but many got it wrong and suffered the consequences. Moreover, there was no "venture capital" in this age. Banks and other financial institutions rarely risked their funds on the new technology. Much of the fixed capital in which the firms invested—the purchase of buildings and equipment—came from retained earnings, that is, the owner's own resources.

Why were factories necessary? Part of the answer must be that the minimum scale of production increased for a variety of reasons. Power was cheaper, horsepower for horsepower, in larger steam engines. Most machines had a minimum efficient scale that exceeded the small size of household labor, even if augmented by apprentices. Heating and lighting, inventory management, and, least appreciated of all, the growing requirements of engineering and technical knowledge made for economies of scale. This was not true for all industries, not even for all "new" industries; what is now known as flexible specialization held its own in many industries. Mass production required the design, construction, and maintenance of machines that could not be mass-produced themselves; but in some cases, deliberate choices were made to specialize in mass-produced factory-made goods. The custom-made products of self-employed, highly skilled specialists required less machinery and provided fewer scale economies but also avoided some of the more egregious excesses of the factories and the early industrial towns. France chose a trajectory that, compared to Britain, was along more traditional lines.

Physical economies of scale were not the only reason why factories emerged. The putting-out system could work only if its employees could be paid a piece wage, as employers could not monitor the time employees spent working. For many products this system was becoming increasingly difficult to follow because of a finer and finer division of labor or because the monitoring of the quality of the product was getting harder. As products became more sophisticated, and markets expanded, the need for standardization was felt more acutely. Manufacturers realized that direct and continuous monitoring of production workers to conform with product specifications was necessary. Furthermore, as technological changes became more and more frequent, workers had to be trained on the job, instructed in the use of new tools and equipment. The emergence of factories thus was partly due to the economics of information. However, more must have been involved because even when workers were paid a piece wage, they were often put in mills and worked under supervision. The expensive equipment owned by the master needed to be

tended with care; raw materials and fuel had to be protected against pilfering. Factories, then, offered many advantages, and no single explanation will do for all cases.

Consideration of why the Industrial Revolution occurred at all needs to be split into why it happened when it did, why it happened in Britain before anywhere else, and why it took the form it did. These three questions are likely to have different answers. The timing clearly has something to do with the ability of inventors and engineers to crack technical problems that were beyond them a century earlier. It is also argued that the timing depended on the existence of a market in which the new products could be sold. Up to a point, this latter argument must take into account that the products pretty well sold themselves through lower prices and higher quality. Perhaps the really important question is not one of why did the great inventions of the 1760s and 1770s take place, but why the wave of technological progress did not peter out after 1815 or so, as it had always done in the past. As to why it happened in Britain, as opposed to some other economy, there is a large and lively literature on the "British advantages," ranging from Britain's good fortune of having large supplies of iron and coal, to its being an island, that—almost alone in Europe—saved it from the invasion of foreign armies. Above all, however, Britain had the kind of institutions that were conducive to economic development and technological progress. Its government was by no means laissez-faire, but it supported innovating entrepreneurs and inventors against the fury of artisans and domestic workers who tried to protect their turf. The British government opposed the conservative forces who petitioned Parliament for legislation to prohibit the new machines or tried to stop mechanization by breaking the new devices and threatening with violence those who intended to employ them. Britain was comparatively peaceful, it had good internal transportation, and its social institutions above all respected private property. Laws, contracts, and ownership could be and were enforced. Labor and capital were relatively free to move around and deployed wherever their return was highest. Furthermore, British culture, more than others, recognized commercial and industrial success as a legitimate source of social status, and members of its elite were often fascinated with the mundane technical details of farming, bridge building, and pumping.

The significance of the Industrial Revolution in economic history cannot be overestimated. Its immediate effect was to establish Britain as the leading economic and technological nation in the world, with all the political prestige and power that came with that, and it imposed the *Pax Britannica* on Europe for a century. Beyond that, it changed the parameters of economic change. Growth before the Industrial Revolution had been usually short-lived, a passing episode that with luck might propel an economy to a somewhat higher plateau. After 1830, it became a permanent condition of those economies that followed the British example and continually introduced new techniques into their production processes. New technology acquired increasing importance in the process of growth. Before 1750, most economic growth, when it occurred, was the result of institutional improvement that permitted trade where none had existed before, or secured better property rights that allowed people actually to enjoy the fruits of labor and patience. Technological change did occur, but its role in growth as such was probably modest. During the Industrial Revolution and after, growth became increasingly dominated by improvements in technology. As people increasingly realized, this was the one form of economic growth that did not run into diminishing returns, that did not slow down, and that could sustain itself.

Not all countries that emulated Britain followed its precise technological example. Some specialized in upmarket, high-quality products. Others relied on different sources of energy, such as water or wind, or found niches in specialized industries. The Industrial Revolution, however, was not about one technical detail or another. It was about the willingness to use a growing understanding of nature (physics, chemistry, biology) in industrial production, implemented by private enterprise, for the sake of profit. It was about the ability of capitalists to mobilize capital and labor on a large scale to introduce these new techniques. It was this feature of the Industrial Revolution that prepared the ground for modern economic growth and the unprecedented prosperity it has brought to much of humanity, a prosperity that would have been unimaginable anywhere in 1750.

[*See also* Patents *and* Technology.]

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