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THE INDUSTRIAL REVOLUTION

A Very Short Introduction

OXFORD

Chapter 3

Why the Industrial Revolution was British

The Industrial Revolution was Britain's path breaking response to the challenges of the first globalization launched by the voyages of Vasco da Gama and Christopher Columbus.

There were several connections. First, the growth in world trade brought new products to Britain including Chinese porcelain and Indian cotton cloth. They were in high demand, and British firms sought to imitate them. Second, the growth in trade and empire opened new markets for British products, and the ensuing expansion of production and commerce generated unusually high wages and cheap energy. How to compete in that environment was the overriding engineering challenge that British industry so creatively met. Third, the commercial expansion and the rise in wages aided British industry in meeting the challenge of foreign competition by improving the health and strength of the workforce and by raising the returns to education and skill. The result was a rise in literacy, numeracy, and trade skills that underpinned the manufacturing sector.

The Industrial Revolution also drew strength from another source that had little to do with globalization—the Scientific Revolution of the 17th century. It contributed both new knowledge—in particular, the discovery of atmospheric pressure and the vacuum—and new attitudes and practices. People came to study the world, including technology, 'scientifically', and that approach brought rewards in the realm of invention. Breakthroughs were due to 'macro inventors', who thought outside of the box and created wholly novel technologies. The macro inventors were often leading scientists or were influenced and informed by them as students, associates, or friends. Many people were connected to the scientific vanguard through networks that diffused the knowledge and attitudes of the Enlightenment across a broad swath of British society, making it more technologically creative. The Royal Society, founded in 1660, was at the apex of this network, which also included provincial associations like Birmingham's Lunar Society as well as a myriad of coffee houses and similar venues where scientific demonstrations were performed. These communication channels, as well as the widely held belief that technology could be advanced by observation and reason, is referred to as the 'Industrial Enlightenment'. The formation of those networks and the adoption of those attitudes could, of course, have been responses to an increase in the profitability of invention, but proponents of the Industrial Enlightenment view of the Industrial Revolution see it as a cultural development whose origin lay in the Scientific Revolution and the broader Enlightenment rather than in economics.

Cotton

The cotton industry is a prime example of the transformative effect of Asian imports on the British economy. In the 17th century, the East India Company began shipping Indian calicos and muslins to England, and the fabrics were so popular that attempts were made to imitate them domestically. In the early 18th century, complicated and shifting import restrictions were introduced to protect the English woollen industry from Indian competition. These restrictions had the unintended consequence of creating a sheltered niche in which an English handicraft cotton industry could begin to operate. Its cloth was exported to Africa where it was bartered for slaves and competed against Indian calicos. English production remained small scale, however, until the production process was mechanized.

This got underway in the 1760s in spinning and printing but was not completed until the 1840s when the power loom drove the handloom out of business. By 1850, cotton employed one-sixth of the manufacturing workforce and accounted directly for 8 per cent of GDP. Eric Hobsbawm caught an important truth when he wrote ‘whoever says industrial revolution says cotton’.

While the Industrial Enlightenment was present in the potteries and in the development of steam power, it was peripheral to the cotton industry, for the inventors in cotton were principally artisans without Enlightenment connections. Samuel Crompton (1753–1827), the inventor of mule spinning, was the son of a part-time farmer and weaver. While a youth, he was taught spinning and weaving. He attended school where he excelled in mathematics. This was typical of textile inventors and attests to the importance of widespread education. From the age of 16 he worked in secret for a decade to improve spinning machines. Apart from the textile trade, his activities were centred around the New Jerusalem Church, a Swedenborg congregation, rather than Enlightenment institutions.

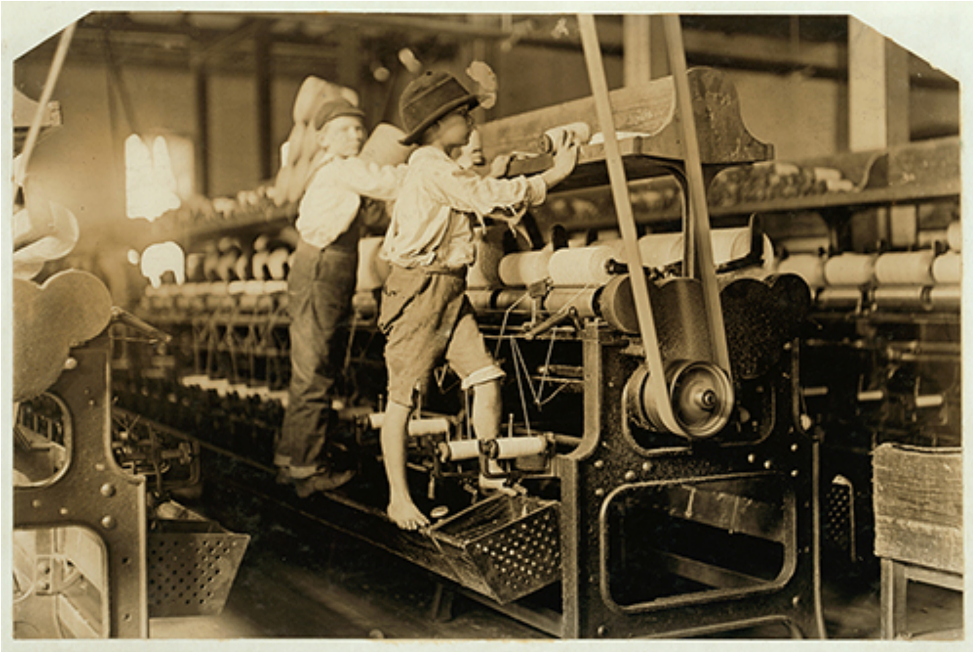
Machinery was the secret of success in the cotton trade. It was developed in Britain in response to the country’s high wages and gave Britain a competitive advantage for decades. The three main branches of the trade—spinning, weaving, and finishing—were all mechanized.

Once calico imports from India proved there was a market for cotton, hand spinning was begun. Merchants brought raw cotton to women who spun it on wheels in their cottages in return for wages (see Figure 7).

7. Irish cottage with handloom weaver and spinner.

The hours of labour to spin a pound (lb) of cotton increased with the fineness of the yarn. Wages were much higher in Britain than in India with the result that Britain could compete successfully with India only in the coarsest yarns, which required the least labour. To produce finer yarn, British firms needed to economize on labour, and that could only be done by inventing machines.

Many Britons responded to the chance to make a profit by trying to invent spinning machines. John Wyatt and Lewis Paul almost succeeded with roller spinning in the 1740s and 1750s, but their Birmingham mill ultimately went bust. James Hargreaves perfected his jenny in the mid-1760s, and it was the first successful machine. He was inspired by watching a spinning wheel rotate after it had fallen on its side. Afterwards, he contrived to run a row of vertical spindles off a common horizontal wheel using wooden clamps to pull the yarn in imitation of the spinner's fingers. In 1767, Richard Arkwright hired John Kay, a clockmaker, to make a machine using rollers, which took five years to perfect. Both Hargreaves and Arkwright also invented carding machines to prepare the cotton for spinning. Arkwright established a factory at Cromford to house his machines (see Figure 8).



8. Factory spinning.

He improved the layout when he built his second mill, and it became the prototype for cotton mills in Europe and the USA. A decade later, Crompton combined elements from Hargreaves' and Arkwright's designs to create the mule, which became the principal spinning machine in Britain in the 19th century. Once in operation, of course, the spinning machines were improved through 'learning by doing' as engineers observed their operation and perfected them. Hargreaves' and Arkwright's machinery made Britain the world's low cost producer of coarse yarn, and the mule made Britain the low cost producer of fine yarn as well.

A much debated question is why these inventions were made in England rather than in France or India. An economic explanation turns on wages and machinery prices. The first spinning machines were an expensive way to save labour and not very good at it. In the late 18th century, spinners' wages were much lower relative to the price of equipment in both France and India than they were in Britain. The early spinning machines were profitable to use in Britain because the value of the labour they saved was high relative to the cost of the machine. They were not worth using on the continent or in India since the value of the labour they saved was very small relative to the cost of the equipment. Early spinning machines were profitable to use in Britain but not abroad, and that is why the Industrial Revolution was British.

History repeated itself in weaving. Hundreds of spinning mills were erected in the 1780s. The price of cotton yarn dropped sharply, and the weaving industry expanded to process all the yarn. Weaving, however, remained a cottage industry using traditional handlooms. Employment exploded, reaching a quarter million (10 per cent of the adult male workforce) in the early 19th century. As the labour market tightened, the wages of the weavers also leaped up, and the 1790s and first decades of the 19th century witnessed 'the golden age of the handloom weaver'. The Reverend Edmund Cartwright, the only cotton inventor with arguably Enlightenment connections—he came from a landed family, attended Magdalen College, Oxford, and was a member of the Society of Arts and the Board of Agriculture—thought it would be simple to design a weaving machine. He was inspired by automatons—the clockwork dolls that mimicked the movements of humans. If a mechanical woman could play a harpsichord, perhaps she could also weave calico? The task proved to be immensely complex. Cartwright wasted his family's fortune working on it for decades, and other inventors took up the challenge. It was not until the 1820s that the power loom was improved sufficiently to challenge the handloom weavers.

In both spinning and weaving, the cottage mode of production contained the seeds of its own destruction. When the cost and demand situation was favourable, the cottage mode responded with large increases in employment and output. As employment approached the limits of the available labour force, the earnings of people with the necessary skills rose, and those high wages became the target of inventors, for the high wages meant that even comparatively poorly designed machines could turn a profit.

Weaving was not the final stage in the manufacture of cloth. It had to be finished.

Much of the enthusiasm for Indian calicos in the 18th century stemmed from the brightly coloured designs that decorated the cloth. The English imitated the look with different methods. Indian cloth was usually hand painted, while the English used a more capital intensive approach. Initially patterns were printed from wood blocks with the result that 'the drawing of one clever designer could be reproduced by many less skilled workmen, whereas the Indian must both design and execute his own work'. By the 1760s, copper plates had replaced the wooden blocks, but the latter were still general on the continent.

Numerous attempts were made to make the process continuous by printing from cylinders. Commercial success was achieved in 1783 with Thomas Bell's design.

The course of invention in all branches of the industry responded to the high wages earned by British workers in the 18th century. Wherever possible, the British opted for a more capital intensive method than the Indians employed. In Britain, the savings in labour costs outweighed the increase in capital costs since wages were high. That was not true in other countries with lower wages. As a result, machine technology cut production costs in Britain without conferring the same advantage on its competitors. The upshot was that by the 19th century, Britain had the most competitive cotton industry in the world.

Britain's share of world cotton textile production rose from a negligible fraction in 1750 to 30 per cent in 1880. Much of this expansion was at the expense of producers in Africa, the Middle East, and India.

The invention of the factory

Textile machinery was housed in mills, and cotton mills were the most common type of factory in Britain in the 1780s. Factories were hallmarks of the new age, for they implied many wage labourers working together on a single site rather than self-employed artisans toiling in their separate cottages. A centralized power source driving the machinery was one reason why production was concentrated, but it was not the only one. The division of labour, skill acquisition, supervision, and quality control were other considerations. The growth of the cotton industry gave a big boost to the factory, and the factory mode of production was adopted in many other industries as well, so it deserves a further look.

Making hats was an unglamorous industry that nonetheless achieved a high rate of productivity growth. This was achieved with the factory mode of production.

The Christy hat factory in Bermondsey in the early 1840s is a good illustration. The factory employed 1,500 people and was the largest hat factory in the world. This establishment 'well illustrates the economy of a large factory' in two respects. The first was effective organization—'the concentration of many departments within the walls of one establishment, the division of labour, the exercise of delegated authority by foremen to each department, and a general supervision of the whole by the proprietors'. The second source of high productivity was the use of machinery. The factory had a 10 horsepower (HP) steam engine that drove machines located around the site via a system of shafts and belts. Some tasks had been mechanized while others were done by hand and relied on the skill of the workers.

When wool entered the factory, it was washed—apparently by hand. Water was expelled, however, from the wool with a large screw press. The wool was dried and then it was carded with the kind of machine used in the textile industry. Likewise, furs were washed and their large hairs were removed. This was a hand operation.

> A number of women, seated on stools, are employed in pulling out the coarse outer hairs from the skins … Each woman lays a pelt on her lap, or on a low bench, and, by means of a knife acting against the thumb, tears out the larger hairs.

Next, the fur was removed from the pelts, again by women, but now operating power driven cutting machines that sliced off the hairs. The fine hair was separated from the coarse hair with a centrally powered blowing machine. A fan turned at 2,000 revolutions per minute, and the air blast carried the lighter fur further than the heavier fur, thus effecting the separation. The next step, in which wool and fur were turned into felt, depended on highly skilled labour rather than machinery. The materials were laid on the bench,

> and the bower, grasping the staff of the bow with his left hand, and plucking the cord with his right … causes the cord to vibrate rapidly against the wool and fur. … All the original clots or assemblages of filaments are perfectly opened and dilated, and the fibres, flying upwards when struck, are by the dexterity of the workman made to fall in nearly equable thickness on the bench, presenting a very light and soft layer of material

ready for felting. 'Simple as this operation appears to a stranger, years of practice are required for the attainment of proficiency in it.' The production process continued to alternate between highly skilled hand activities, less skilled activities, and machine processes until the hats were completed.

The Bermondsey factory illustrates the subdivision of production into a sequence of tasks requiring different degrees of skill, which were acquired through experience, and which were remunerated at different rates. Quality was checked by supervisors, and machinery was installed where a high capital labour ratio lowered costs. We know that the degree of mechanization was carefully thought out. In the 1830s, wages in the USA were already higher than in the UK, and American hat manufacturers had invented a more highly mechanized system than Christy's employed. Although Henry Christy was familiar with American technology from 1833 at the latest, his firm did not adopt the full-blown American system until the 1860s, in part, as he explained, because 'the rate of labour is much greater and the savings consequently greater' in the USA than in the UK.

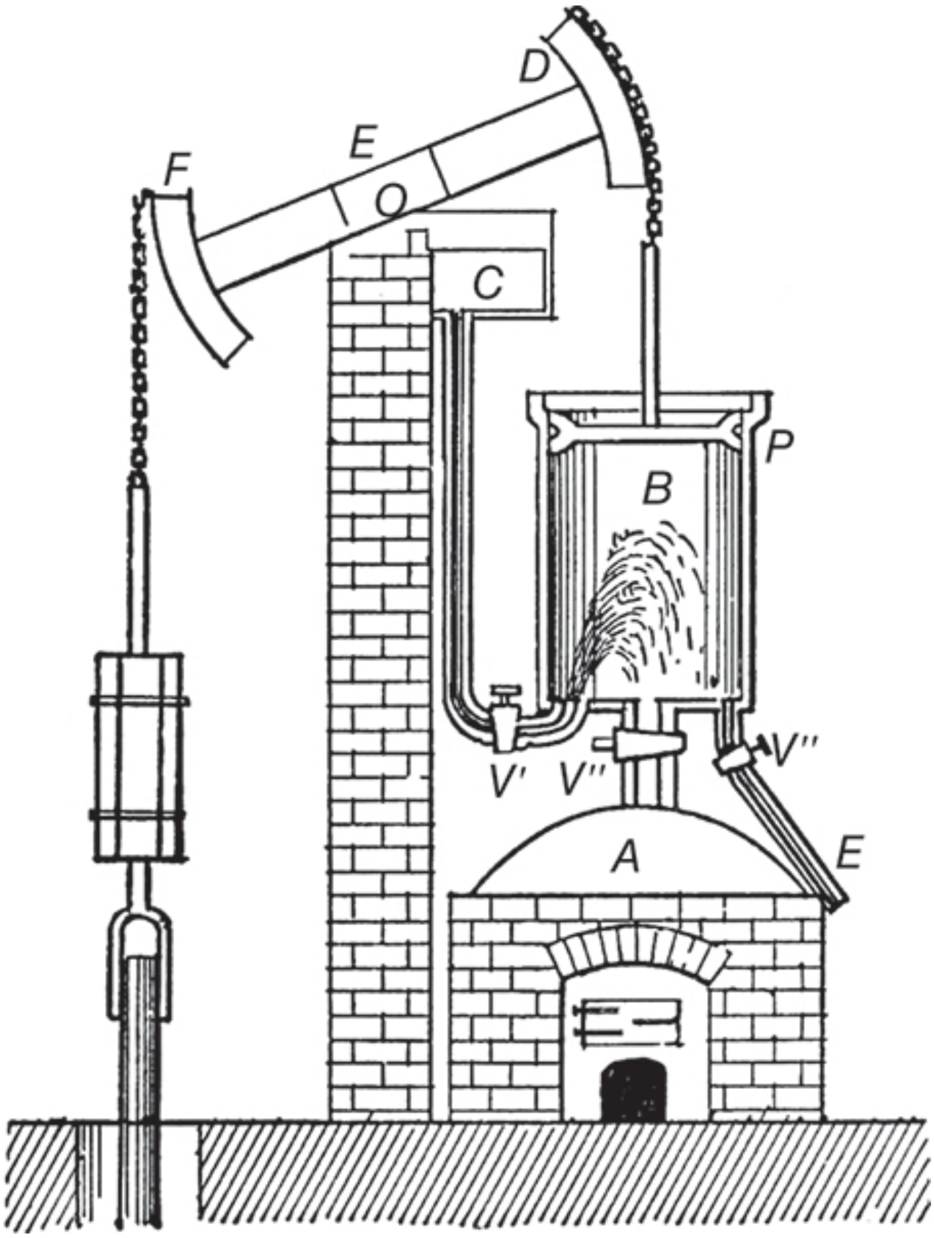
Steam

Energy in the pre-industrial world came from the exertions of humans and animals, from burning organic fuels like firewood and charcoal, and from the power of wind and flowing water. Modern economic growth required more potent sources and the first to be harnessed was coal. Initially, it was burnt for heat in London in the late 16th century. In the 18th century, coal's thermal energy was converted to mechanical power through the steam engine. Pumping water out of mines was the first application. Engines were gradually improved in the next hundred years, but their economic impact was slight until the development of efficient, high pressure engines around the 1830s. These were applied widely to power industry and transportation. By the middle of the 19th century, the revolutionary potential of steam power was realized, and it made a significant contribution to economic growth.

The invention—and perfection—of the steam engine was closely connected to the Scientific Revolution, both in terms of the application of new knowledge and in terms of cultural and institutional connections to the scientific establishment. The wide availability of schools and technical training through apprenticeships were also important since the development of steam technology required many artisans and engineers from modest backgrounds.

The steam engine was an important application of knowledge discovered by 17th-century scientists. The science began with Galileo, who was the first to suspect that the atmosphere had weight. The idea occurred to him when he studied the problem of draining mines, and he noticed that suction pumps would not lift water more than about 30 feet. He got his secretary Evangelista Torricelli to work on this problem. Torricelli invented the mercury barometer and weighed the atmosphere. In 1672, von Guericke of Magdebourg weighed the atmosphere with a vertical cylinder containing a piston rising from the top of a cylinder. A rope was tied to the piston and looped over a pulley and held a platform on which van Guericke put weights. He found that by pumping the air out of the cylinder, the atmosphere pushed the piston down and raised the platform. He could offset that rise and weigh the atmosphere by putting weights on the platform. In 1675, Denis Papin eliminated the vacuum pump by filling the cylinder with steam and then condensing it. Papin had invented a proto-steam engine.

The von Guericke experiment was similar to the first successful steam engine invented by Thomas Newcomen in 1712 (see Figure 9).



9. Diagram of Newcomen steam engine.

Newcomen's engine also had a vertical cylinder and piston. Instead of the pulley, there was a balance beam, and the weights were replaced with a pump to drain water from a mine. By filling the cylinder with steam and then condensing it with a squirt of cold water—Newcomen's famous 'cold water injection'—the atmosphere pushed the piston down and raised the pump. Newcomen had found a way to raise water—and make money—from the weight of the atmosphere.

At one time, historians of the steam engine thought that Newcomen was wholly innocent of the science of the atmosphere, but in recent years that view has shifted, and it is now recognized that Newcomen probably did know what natural philosophers had discovered. The conduit was Thomas Savery, Fellow of the Royal Society, who knew the science. Savery invented a steam pump and visited Dartmouth to promote it. He probably met Newcomen there. They certainly had at least one friend in common. So it is likely that one of the greatest inventions of the Industrial Revolution really was science in action.

The science underlying the steam engine was pan-European (the leading scientists were Italians, Germans, and French), but the research and development (R&D) was carried out in Britain by an Englishman. The reason is that Britain was the only place where it was profitable to use the engine on a large scale, for two reasons. First, the main use of the engine was to drain mines, and Britain had the largest mining industry in Europe thanks to coal. Second, the engine used prodigious amounts of fuel, and coal mines offered cheap fuel. John Theophilus Desaguliers, a leading engineer in the early 18th century, observed:

> where there is no water [for power] to be had, and coals are cheap, the Engine now call'd the Fire Engine, or the Engine to raise the Water by Fire, is the best and most effectual. But it is especially of immense service (so as to be now of general use) in the Coal-Works, where the Power of the Fire is made from the Refuse of the Coals, which would not otherwise be sold.

The reason it was profitable to develop the Newcomen engine in Britain was because there were coal mines to be drained.

Newcomen's engine was the macro invention that began a technological trajectory.

In the next century and a half, the engine was perfected by many of the most famous engineers of the Industrial Revolution. Consumption of all inputs was reduced including coal, which was cheap in Britain. Fuel consumption dropped from 44 lbs of coal per HP-hour in 1727 to 3 lbs in 1847. This improvement was a triumph for British engineering, although it undermined the country's competitive advantage by turning the steam engine, which had mainly benefited Britain in the 18th century, into a technology that could be used anywhere in the world. Once the coal consumption was reduced to 3 lbs per HP-hour, the price of coal was of little importance to the commercial application of the engine. British engineers had invented the 'appropriate technology' for everyone else.

An intellectual result of the Industrial Revolution was the image of the inventor as an Inspired Genius. This was no accident: middle-class propagandists promoted James Watt as a genius of invention—and, thus, a guarantor of the nation's prosperity—as a counter to the military genius of the Duke of Wellington, who not only defeated Napoleon but then became the political leader of the landed classes. In fact, invention occurred in many ways besides a genius having a brilliant idea. Much of invention consisted of painstaking engineering that turned often banal ideas into products or processes that worked reliably and cheaply. This was certainly the case in textiles. Thomas Edison's quip that 'invention was 1% inspiration and 99% perspiration' contained an essential truth. 'Learning by doing' was also important as engineers and managers observed how machines and production processes worked in practice and found ways to improve them. Sometimes businesses exchanged information (intentionally or otherwise) so that the advances made by one firm could be carried forward by another. The result was collective invention.

The history of the steam engine illustrates the different ways in which invention can be organized, and the importance of both the elite inventors of the Enlightenment and artisan inventors without connections to high level science. The steam engine was invented by Newcomen, a Dartmouth ironmonger, who did secure a patent in conjunction with Thomas Savery, FRS (Fellow of the Royal Society), to realize some gain. Fuel consumption fell from 44 lbs per HP-hour in 1727 to 30 lbs per HP-hour in 1769, probably because of collective invention as operators shared their results and built on each other’s experience.

Consumption dropped again from 30 lbs to 17 lbs. This was the result of research by John Smeaton, FRS. Smeaton collected the records of fifteen engines—their owners did not keep them secret—and analysed them to determine the most efficient design. Smeaton did not patent his findings. He profited from his research through consulting contracts. Smeaton was a leading light in the Industrial Enlightenment.

The next advance was due to James Watt, FRS, whose famous separate condenser cut fuel consumption from 17 to 9 lbs. The first engine with a separate condenser went into service in 1776. Watt was certainly motivated by personal gain and obtained a patent on his condenser in 1769. Watt’s career illustrates the two-fold nature of patents: it provided him with a reward for invention, but it also stifled later progress since he used his patent to prevent other inventors from experimenting with compounding cylinders. Engineering progress was retarded until Watt’s patent expired in 1800.

Watt is also an example of the importance of social connections linking scientists and practical engineers. Watt was born in Greenock and was sent to Glasgow at the age of 18 to learn the trade of mathematical instrument maker. He stayed initially with his mother’s family, and it was through her relative George Muirhead that Watt was introduced to members of Glasgow’s scientific and cultural elite. He became a close friend of Robert Dick, future Professor of Natural Philosophy, and Dr Joseph Black, Professor of Medicine.

After a year’s training as an instrument maker in London, Watt returned to Glasgow in 1757 and was allowed to open a workshop at the university where he made instruments for Joseph Black. Black’s scientific research concerned heat, and he conceived the concept of ‘latent heat’, which he offered to Watt as an explanation for the success of his separate condenser.

Later Black took a chair at Edinburgh and set himself the task of developing the Scottish economy by applying scientific knowledge. He worked with industrial entrepreneurs. Black became a lifelong friend of Watt. Watt raised capital for his business ventures by forming partnerships with Black and other members of Black’s circle like John Roebuck, who also hired him to erect one of his first steam engines at a coal mine in Kinneil. The Scottish scientific-industrial complex is the premier example of the Industrial Enlightenment, and Watt took advantage of its connections to deepen his ideas and further his inventions.

The next advance in steam power was effected by Cornish engineers who designed the famous Cornish pumping engines to drain copper and tin mines. Their goal was to save fuel, which was very expensive since coal was brought from South Wales. The problem was heightened by the expiry of Watt's patent in 1800, for Watt then withdrew his engineers from Cornwall, and engine efficiency dropped sharply. The mine owners did not want to pay Watt for advice, so they banded together to solve their problems themselves. Details of design and fuel consumption for all engines were ascertained monthly and published in *Lean's Engine Reporter*. In that way, engineers could learn from each other's experience, and Cornish engines were perfected over the next decades. This was collective invention on a grand scale, and it created the most efficient pumping technology ever seen. Patents were not necessary for progress. The engineers who accomplished these improvements did it without Enlightenment connections.

Ceramics

Porcelain is a prime example of the way in which Asian imports stimulated the Industrial Revolution. In the medieval and early modern eras, China had a large porcelain industry that exported exquisite vases, platters, and other goods around the world. Many of these were decorated with blue patterns on a white background, although other colours were also used. Porcelain production was initiated in England in the mid-18th century.

Starting a ceramics industry in a new country at that time was technically difficult since chemistry was in its infancy, which meant that the properties of the local raw materials could not easily be determined nor could the production methods be adapted through routine scientific methods. Knowledge of these matters was tacit and embodied in the artisans in the industry. These challenges were met through a stream of improvements starting in the mid-17th century. After foreign products were successfully imitated, progress was pushed forward by both famous and less well known potters.

The history of ceramics also lends support to the Industrial Enlightenment view that the advance of science gave impetus to technical progress through contacts with leading scientists and (more importantly) through the application of the scientific method to the perfection of manufacturing methods. Indeed, ceramics was one of the first industries in which modern, scientific knowledge replaced the artisan's tacit understanding.

In the mid-17th century, English ceramic production was in a primitive state. Most domestic production was cheap, locally produced earthenware. High end demand was met with imports of Chinese porcelain, and substantial quantities of salt glazed stoneware were imported from the Rhineland and sold to middle and lower class households.

The first steps towards establishing a British industry were taken by John Dwight (1633–1703), who is an excellent example of the Industrial Enlightenment pushing technology forward. Dwight was the son of a yeoman but had such academic promise that he was admitted to Oxford University where he studied law and chemistry, and worked in Robert Boyle's laboratory. He took his degree in law, however, and worked as an ecclesiastical official until 1669 when 'having tryed many experiments he concluded he had the secret of making China Ware. Thereupon he sold his [clerical] Office, came to London, was encouraged therein by Mr Boyl and Dr Hook.' He tried to manufacture all types of pottery imported into Britain. While he was unsuccessful in producing porcelain, his experiments unlocked the secret of manufacturing salt glazed stoneware. This was no mean achievement since it required the identification of suitable raw materials, the invention of a high temperature furnace, and discovery of the correct method of applying the salt glaze. Dwight patented his process and tried to keep it secret but was unsuccessful as his employees quit and founded competing firms. Dwight was responsible for the establishment of the salt glazed stoneware industry in England.

China exported porcelain across Eurasia, and people in many countries tried to produce it locally. The Ottoman Turks, for instance, made a fritware imitation. In the 15th century, potters in Iznik created a novel process using local materials that featured doubly fired cobalt blue patterns on a white underglaze. In the next two centuries, they expanded the colour range and exported large quantities to the Middle East and Europe. In the 18th century, however, the industry slid into decline without sparking an industrial revolution. In Europe, August the Strong, Elector of Saxony, was an avid porcelain collector and promoted research by Ehrenfried Walther von Tschirnhaus (another example of the Industrial Enlightenment, although a German) and the imprisoned alchemist Johann Friedrich Böttger. In 1708, they succeeded in making true porcelain, Saxon sources of China stone and China clay were discovered, and the Meissen industry was born.

In England, it was another exemplar of the scientific culture, William Cookworthy (1705–80), who finally succeeded in producing hard paste porcelain. He was a successful apothecary. In the 1740s, he discovered deposits of China stone and China clay in Cornwall on land owned by Thomas Pitt, nephew of William Pitt the Elder and later First Baron Camelford. Pitt was not notable for his scientific interests, but he did finance Cookworthy's patent application and the experimental work to perfect the manufacturing process—presumably to raise the value of the minerals on his estate. Cookworthy had numerous scientific acquaintances including John Smeaton, who lodged in his house while building the Eddystone lighthouse (1756–9) and Captain James Cook and Joseph Banks, who dined with him in 1768.

Josiah Wedgwood (1730–95) was another paradigm of the Industrial Enlightenment, and he took English manufacturing to even higher levels of sophistication. His family were potters, and he was apprenticed to the trade. Nonetheless, he picked up the scientific idea that knowledge was gained though experiments, and he conducted 5,000 to find better materials and processes. He invented a pyrometer to measure temperatures more accurately, which led to his election to the Royal Society. He established a successful manufacturing business and led the industry in introducing new products like Queen's ware (an improved creamware), basalt ware, and jasper ware. As well as tableware, he produced medallions, ornaments, and vases. He was a great marketeer.

Dwight, Cookworthy, Wedgwood … This looks like the Industrial Enlightenment in action. However, while these lunimaries made decisive contributions to the development of English pottery, they were not alone. The set of inventors was broader in two respects. First, many inventions were made by people with only trades backgrounds and without Enlightenment connections. Wedgwood made his early money selling creamware, which became a staple of the English potteries for a century. Creamware was invented by Enoch Booth in the 1740s. Booth was the son of a butcher and apprenticed to a potter. Booth also invented the double firing process around 1750. He was the first to glaze a pot, fire it, paint a picture on the surface, and then fire the pot again with a clear glaze on the exterior to protect the image. Another inventor from a humble background was Josiah Spode I (his grandfather was a 'coal getter') who apprenticed with Thomas Whieldon. Spode perfected under glaze transfer printing in 1784 and developed bone china, a project that was finished by his son Josiah II. The famous inventors like Dwight and Wedgwood worked in an industry made up of independent artisan producers many of whom were making equally valuable contributions to technical progress. Indeed, one might try to subvert the Industrial Enlightenment by reclaiming Wedgwood for the artisans. He was, after all, engaged in his experiments on ceramics when he was only 24 years old and working with Thomas Whieldon. Wedgwood did not read his first paper to the Royal Society until he was 52. From the point of view of the artisans, the Royal Society showed good taste in celebrating one of their leading lights, but the impetus for his discoveries and achievements came from below, not from above.

Second, pottery technology developed through collective learning as well as through the efforts of inspired geniuses and R&D entrepreneurs. While artisans often tried to keep their improvements secret, this proved difficult since employees took the knowledge with them when they left the firm. The result was collective invention despite the efforts to suppress it. Technological progress in ceramics did not depend exclusively on the deeds of leading figures. The pervasiveness of collective invention is a second qualification that must be made to the inspired genius model as applied to the potteries.

It was one thing to design pretty pots, but it was another to make them cheaply.

Innovation in pottery was directed as much towards the latter as the former. England developed methods that differed fundamentally from those used in China. In both countries, technology evolved in the direction of reducing the use of expensive inputs while increasing the use of cheap ones. First, English manufacturers reduced the employment of skilled labour by adapting machinery developed for other industries. Wedgwood, for instance, installed lathes to turn the cylindrical parts of vases. Second, transfer printing was invented. In China artists painted the design on each piece. This was the first system used in England. It was very expensive. Transfer printing cut costs in England by substituting capital for labour. In transfer printing the design was engraved on a copper plate, which was then used to print the pattern on tissue sheets. While the ink was still wet, a sheet was laid on a previously glazed pot to which the ink then adhered, transferring the design to the pot. John Sadler, an English printer, and John Brooks, an Irish engraver, independently invented the process in the 1740s. The ink, however, wore off. The solution was to apply a second layer of glaze over the ink image and fire the pot again. John Wall, a physician and founder of the Worcester Porcelain Company, developed transfer printing with blue ink under glaze in 1757, and John Spode refined the technique, as noted, in 1784. The famous blue-on-white willow pattern, first engraved by Thomas Minton in 1780, was a transfer print (see Figure 10).

10. Plate decorated in willow pattern.

Third, although capital was substituted for expensive labour in the English potteries, it was not used indiscriminately, as a comparison of English and Chinese kilns shows.

English kilns were built to economize on capital and were profligate in their use of energy. English-style kilns had a coal fire in the bottom. The heat rose, enveloped the pots, and then vented out of the furnace through a hole in the top. Much of the energy was wasted. The English kiln was cheap to build but not thermally efficient. In contrast, the Chinese kilns used lots of capital to preserve energy. They consisted of a series of chambers rising up a hillside. A fire burned at the entrance to the lower chamber where the heat was drawn in to bake the pots. The heat was not vented out of a hole in the top in the English manner. Instead, it was forced down through a hole at floor level and entered the next chamber up the hill. The heat was reused in chamber after chamber, so it was not wasted. This design, of course, equated to more capital. Pottery kilns, therefore, are another example of the way in which technology was designed in response to the cost of capital, fuel, and labour. In this case, expensive fuel in China led to the substitution of capital for energy, in contrast to English practice.

The final avenue by which the English cut costs was in the growth of factory production in the potteries. Wedgwood's Etruria mill was a leader. It was based on the division of labour, but, unlike cotton weaving mills, the aim was less to substitute unskilled women and children for male artisans, and more to upgrade skills by training people for artistic jobs. In addition, machinery was used, as noted, to raise labour productivity in tasks that could be done by lathes, for instance. Finally, inspection and quality control were obsessions.

The end of the Industrial Revolution

In some accounts, the Industrial Revolution ended around 1830, but in our view it had another generation to run. The progress achieved by 1830 was far from balanced. The cotton industry was very large; spinning was wholly mechanized; and the power loom was forcing the handloom onto the scrap heap of history. The technology of iron production had also been revolutionized, and an engineering industry had developed that supplied machinery mainly to the textile industry. There was some progress outside of these sectors—machinery was used in the production of candles and hats, as we have seen—but much of the economy was as yet untouched.

This situation changed between 1830 and 1870 as modern technology spread across the economy. An important indicator was the growing use of steam. At the beginning of the 19th century, most steam engines were installed in mines for draining. Industry was powered by water. In 1830, steam and water were equally important sources of power with 165,000 HP of each. By 1870, water power had increased to 230,000 HP while steam leaped to 2,060,000 HP. The increased use of steam was due to better fuel efficiency and the development of high pressure engines which were lighter and cheaper than the low pressure engines of Newcomen and Watt.

One advantage of a steam engine was that it was potentially mobile, unlike a water wheel. All early experimenters with high pressure steam tried to power a vehicle, but the results were unsatisfactory due to the poor condition of the roads. One solution was to put the engine on the rails commonly used to bring coal and ore out of mines. Richard Trevithick built the first steam locomotive that hauled minerals on the tramway of the Penydarren Ironworks in Wales in 1804. There was a market for locomotives in collieries, and their designs were gradually improved as engineers tried out alternative configurations and learned from experience. The great turning point was George and Robert Stephenson's

Rocket, which won the Rainhill trials in 1829. They were awarded the locomotive contract for the Liverpool and Manchester Railway, which was the first general purpose railway and inaugurated a frenzy of construction. By 1867, 12,000 miles of track were in operation.

Railways were laid around the world and contributed to the integration of world markets.

Another solution to the problem of bad roads was to put the engine on a boat. Robert Fulton built the first commercially successful steam ship, the *Clermont*, which sailed the Hudson River in 1807. Crossing oceans was a bigger challenge. An issue was, again, the thermal efficiency of the engines, for a ship had to carry the coal it needed for its voyage, so the less efficient the engine, the more carrying capacity had to be devoted to coal rather than freight, which would bring in revenue. Isambard Kingdom Brunel's *Great Western* established that a ship could cross the Atlantic in 1838 and his *Great Britain* was the first iron ship driven by a screw propeller. The transition from sail to steam was gradual and depended on improvements in engine efficiency. By the end of the 19th century, steam finally replaced sail on the longest route from Britain to China. As steam use increased, so did the integration of the world economy.

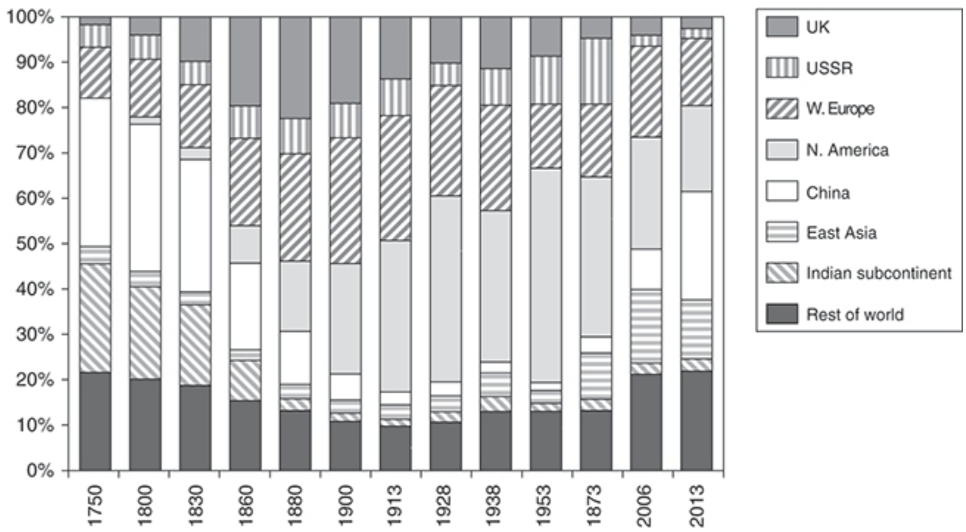
Between 1830 and 1870, steam driven machinery displaced human and animal labour in activities across the economy. Portable steam engines drawn by horses provided power on farms in the 1850s and were superseded by the traction engine (1859). In 1865 it was equipped with a roller and was used for road surfacing. Steam powered sawmills were replacing two men and a saw from the 1820s onwards. The pug mill replaced heavy manual labour in the mixing of clay for brick making and pottery. Bricks were formed with mechanical extruders rather than by hand. And so forth in industry after industry.

Steam power contributed very little to the growth in aggregate labour productivity before 1840. The greatest contribution came between 1850 and 1870, and coincided with the construction of railways and the spread of factories and machines across the range of British industries. Hand work disappeared and was replaced by higher productivity, higher paid factory work in the middle years of the 19th century.

Chapter 6

The spread of the Industrial Revolution abroad

The Industrial Revolution may have ended for Britain in 1867, but it had only just begun for western Europe and the USA and was still a future prospect for the rest of mankind. Its spread is charted by Figure 16, which shows the shares of world manufacturing output produced in different regions.



16. Percentage shares of world manufacturing output, 1750–2013.

These figures are fragile, especially for the early years, but the great industrial revolutions stand out clearly.

In 1750, the biggest manufacturing economies were China and the Indian subcontinent (today's India, Pakistan, and Bangladesh). These were also the most populous countries, and that was no coincidence. Inter-continental trade included few manufactures, so a region's production equalled its consumption. Since per capita income was broadly similar, so was per capita consumption of manufactures. Manufacturing production was, therefore, greatest where population was greatest. For the same reasons, British production of manufactures was less than 2 per cent of the world's total.

The situation changed dramatically due to the Industrial Revolution in Britain. By 1880, Britain's share of world manufacturing reached its peak value of 23 per cent. In contrast, the Indian and Chinese shares dropped to about 2 per cent each and remained at similarly low values until late in the 20th century. These drops were not just relative but represented absolute de-industrialization as British imports destroyed the indigenous Chinese and Indian manufacturing industries. The growth of manufacturing output in Britain during the Industrial Revolution came at the expense of the manufacturing industries of the ‘third world’.

Not all countries experienced this fate. Western Europe’s share of world manufacturing increased from 12 per cent in the 18th century to 28 per cent in 1913—a second industrial revolution. Even more dramatic was the rise of North America, principally the USA. From less than 1 per cent of world manufacturing in the 18th century, the North American share reached a peak value of 47 per cent in 1953. This was an even greater industrial revolution than Europe’s. The growth of manufacturing output in western Europe and North America reduced Britain’s share of the world total substantially.

Two other regions experienced industrial revolutions in the 20th century. One was the countries that comprised the USSR. The Russian Empire had produced 5 per cent of world manufactures in the 18th century, and the Soviet five-year plans pushed the USSR’s share of manufacturing up to 15 per cent in the 1980s. With the collapse of communism, the region’s manufacturing share crashed to only 3 per cent.

The other region that experienced rapid industrial development in the 20th century was East Asia (Japan, Taiwan, and South Korea). The East Asian share dropped from 4 per cent to 2 per cent in the early 19th century, but then increased to 5 per cent, as Japan built up a modern industrial sector in the first half of the 20th century. The economy of the region was destroyed in the Second World War, but rapid growth resumed first in the 1950s in Japan and later began in Taiwan and South Korea. By 2006, these countries were producing 17 per cent of the world’s manufactures.

The final industrial revolution is China’s, and it is a very recent phenomenon. In 1953, just after the communist revolution, China’s share of manufacturing (2 per cent) was at its all time low. By 1980, it had been pushed up to 5 per cent, and it continued to rise reaching 9 per cent in 2006. Subsequent growth has been very rapid and off a very high base, so China’s share hit 25 per cent in 2013. China is now the leading manufacturing economy in the world.

But China is exceptional. Despite much excitement about rapid growth in other countries, their shares of manufacturing output have not advanced. The Indian subcontinent, for instance, produced 2 per cent of the world's manufactures in 1973 and only 3 per cent in 2013. The 'rest of the world', which includes Latin America, Africa, the Middle East, much of eastern Europe, south-east Asia, Australia, and New Zealand, managed to raise its share of world manufacturing from 13 per cent in 1973 to 21 per cent in 2013. This advance is not inconsequential but is not in the same league as the industrial revolutions discussed.

Therefore, the major historical question is: why did some countries have industrial revolutions while others did not?

Globalization and technology: the economics of de-industrialization

The British Industrial Revolution differed from all that came after for two reasons.

First, the British Industrial Revolution was unplanned; indeed, it was unimaginable before it happened. All subsequent industrial revolutions were planned in the sense that countries adopted policies that they hoped would lead to industrial development. Second, all subsequent industrial revolutions have had to contend with the presence of an industrial power that exported at very low cost the manufactured goods they hoped to produce. Would-be industrializers had to meet that challenge—somehow. Indeed, their situation was even more dire. A country that failed to meet the British challenge did not just stand still—it fell behind; in other words, it was de-industrialized.

The economics are clear in one of the earliest cases of de-industrialization—that of India in the early 19th century.

The British Industrial Revolution took place in a world that was becoming increasingly globalized. The establishment of the sea route from Europe to India cut the real cost of shipping and made it possible for the various East Indies companies to profitably export cotton cloth from India to Europe. English producers tried to imitate these cloths.

Since British wages were much higher than Indian wages, British producers had to invent labour saving machinery to sell anything but the coarsest yarn. The spinning machinery greatly increased British competitiveness in cotton textiles, but it conferred no benefit on producers in India or, indeed, on the continent since their wages were so low that machines did not pay. With machines, it was relatively cheaper to produce cotton cloth in Britain than in India, whereas previously the reverse had been true. The theory of comparative advantage predicts that Britain would increase its export of cotton, while India would import cotton cloth rather than exporting it. Britain, in other words, would industrialize, while India would de-industrialize. That is, of course, what happened.

Comparative advantage arguments are abstract. We can see how the incentives changed by studying the evolution of prices in Britain and India. In the late 18th century, the prices in Britain of both English and Indian cloth were much greater than the price of Indian cloth in India, which is why India exported to Britain. By 1820, however, the prices of both cloths dropped sharply in Britain as technological progress cut British production costs, and the falling price of English and Scottish cloth pulled the Indian price down with it.

By 1820, the English price was lower than the price of Indian cloth in India. The structure of trade reversed as Indian cloth exports ceased, and the country began to import British cloth. The result was the de-industrialization of India. It led William Bentinck, the Governor-General of India, to his famous remark: ‘The bones of cotton weavers are bleaching the plains of India’.

India’s comparative advantage shifted from manufacturing to agriculture, and this change shows up in the prices of raw cotton. At the beginning of the 19th century, the price was much higher in Liverpool than in Gujarat. The gap declined as shipping costs fell (globalization in action!), and the real price of cotton rose slowly in India. This price rise led to an increase in cultivation and exports. The underlying economics were clear to contemporaries. The British MP John Brocklehurst asserted in 1840 that ‘the destruction of weaving in India had already taken place … India is an agricultural rather than a manufacturing country, and the parties formerly employed in manufactures are now absorbed in agriculture’.

The story of cotton manufacturing in India is a microcosm of the history of Asia and Africa in the 19th century. By the 20th century, their manufacturing sectors had been destroyed by competition from factories in Britain and later western Europe and the USA. The economies of Asia and Africa were re-oriented to produce and export agricultural products. When development economists surveyed these regions in the 1960s, they assumed that this economic structure was ‘traditional’. It was anything but. ‘Underdeveloped countries’ in the

20th century were made—not born. They were the products of 19th-century globalization and the industrialization of the West.

Catching up in the 19th century: the standard model in the USA

The first question is why the same fate did not befall western Europe and the USA. The answer is that they followed a set of policies comprising the standard 19th-century model of economic development. The model was developed in the USA since the issue was so pressing for the new Republic. In the colonial period, the USA was effectively in a free trade union with Britain and exported agricultural products and imported manufactures. The USA was de-industrialized from the start. How could it break out?

The first step to an answer was creating a government with enough power to act. In the 1780s the states were united in a loose confederacy with limited powers. The USA constitution that came into force in 1790 was intended to create a national government that was strong enough to develop the country. The constitution itself was the first step in that direction, for it abolished the tariffs that the states had imposed on each other's products, thus creating a large domestic market. In his famous *Report on Manufactures* (1791) Alexander Hamilton, the first treasury secretary, outlined policies that were eventually adopted, including transportation improvements to integrate the domestic market; a national bank to stabilize the currency and insure credit for investment; and a tariff to protect American industries against British competition. These policies were dubbed 'the American system' by US senator Henry Clay, and they form three of the four elements of the standard model.

The final element was mass education. The white population of the USA had been highly educated during the colonial period, and the school system was strengthened in the new republic. The Common School Movement in the 1830s led to systems of publicly financed schools focused on assimilating the masses of immigrants by preparing them for industrial employment. Together these measures—create a national market by abolishing internal tariffs and building transportation infrastructure, establish a banking system to promote investment, erect tariffs to protect industry from British competition, and institute mass education to prepare the population for a commercial economy—became the standard model of economic development in the 19th century.

The standard model was put into practice soon after the Constitution came into force.

The federal government built roads like the Cumberland road that connected the east coast to the midwest in 1811–16, and New York State built the Erie Canal between the Hudson River and the Great Lakes in 1817–25. The First and then the Second Banks of the United States were chartered in 1796 and 1816. A protective tariff was also erected in that year in response to peace in Europe, the previous decades of warfare having provided American manufacturing with some protection.

While the Bank of the United States was ultimately destroyed by President Andrew Jackson in the 1830s, the other elements of the standard model were repeatedly reaffirmed. Canals, roads, railways, airports, highways, and super highways have always been constructed by governments or with government support. The educational system has been continuously expanded. The USA maintained very high tariffs, which were controversial in the first half of the 19th century, until the 1960s when it was so preeminent in manufacturing that trade liberalization seemed a better way to secure markets than protection.

America industrialized within this policy context. Industrialization was not difficult once the policy parameters were in place. Wages in America were very high, and that meant that British factory technology was the appropriate technology for the USA. Technology transfer was effortless from the start. By the 20th century, the USA became the world's high wage economy and an important generator of technology. What it invented suited its circumstances. It was other countries that had a problem adapting American technology to their circumstances.

The standard model in Europe

The situation was different on the continent. In the early years of the Industrial Revolution, British technology did not pay since labour was cheaper relative to capital in France or Germany, for example, than it was in Britain. Consequently, hand techniques were more cost effective than Britain's factory technology. Western Europe was in danger of going the way of India.

Manufacturing development did not get underway on the continent until after Napoleon's defeat in 1815. Napoleon had prepared the ground, however, by spreading the reforms of the French Revolution across Europe. These included the abolition of serfdom, expropriation of monastic property, a new legal system (the *Code Napoléon)*, equality of all citizens before the law, the abolition of internal tariffs, modernization of the tax system, the extension of education, and the promotion of science and learning. The French imposed these changes where they ruled, and other countries like Prussia that were defeated but remained independent adopted variants themselves.

In addition to the legal changes, the commercial prospects of factory spinning and steam power were much brighter than they had been in the 1780s because British engineers had been busy making the machinery more efficient. As modern technology became more productive, it undercut hand methods no matter how cheap the labour had been, and that point was reached in western Europe after Waterloo. In the cotton industry, progress was very rapid. Hand spinning had employed 2,500 workers per 1,000 spindles in the 1760s. Arkwright mills cut that to about ninety workers in the 1780s, and by the 1820s British mills employed sixteen workers per 1,000 spindles. It took time, however, to train a workforce, so newly built French mills in the 1830s were employing more workers than British mills—24 per 1,000 spindles—even when they were using modern machinery. These mills were good enough to undercut women using spinning wheels, but they were not efficient enough to compete against British imports in a free trade environment. It was the same situation in Germany. What to do?

Tariffs were clearly needed but were not enough on their own. The whole standard model was required. It was popularized in Europe by Friedrich List's *The National System of Political Economy* (1841). List was a political refugee in the USA in the late 1820s and was influenced by Alexander Hamilton and the results of his policies. Germany provides a good example of the American system in Europe. Similar policies were pursued in France and elsewhere. The Congress of Vienna left Germany divided into thirty-eight states in 1815. Prussia was the largest and its territories were scattered across Germany. To facilitate trade among its regions, it sponsored the Zollverein (Customs Union) with intervening states in 1815. More states joined in the next decades, and the customs union because the basis of the German Empire in 1871. The Zollverein both created a large domestic market by abolishing tolls within Germany and erected a high tariff wall to keep British goods out while German firms established themselves.

Germany followed the other imperatives as well. The national market was strengthened by transportation investment. The first German railway was built only five years after the first British line, and 63,000 kilometres of track were open by 1913. Between the 1850s and the 1870s giant investment banks were established, and these funnelled capital into industry. Finally, a system of universal education was established. This had been started in the 18th century under Friedrich the Great. Indeed, the American Common School Movement was modelled on the Prussian school system.

Economic development was very rapid in Germany after 1870. A coterie of new industries was created—steel, chemicals, electricity, and automobiles are only the most famous. Many of these had a basis in science, and Germany excelled at them. The German educational system from primary schools through technical high schools and universities was more modern than Britain’s, which was held back by its undemocratic constitution. Britain only got universal primary education, for instance, after the franchise was extended to include about 60 per cent of men in the Third Reform Act (1884).

The standard model on the periphery

The standard model was also tried on the periphery but success was mixed. Mexico made half-hearted efforts. In the 1830s a protective tariff was introduced and the proceeds used to fund a small investment bank. The result was thirty-five cotton spinning mills. State tariffs were left in place, so a national market was not created, and education was ignored. The dictatorship of Porfirio Diaz (1877–1911) was more vigorous. The internal tariffs were eliminated and railways built to create a national market. Instead of banks, foreign investment was relied on for capital and to bring advanced technology into the country. Mass education was still ignored. The result was more industrial development based on foreign owned factories and foreign managers with Mexicans doing the menial work. The economic growth that resulted was not rapid enough to tighten the labour market, so real wages stagnated, all the gains from growth went to the rich, and the regime collapsed in the revolution of 1911.

The story was similar in Russia. A large railway network was built between 1870 and the First World War to open up remote parts of the country and connect them to the industrial heartland as well as the principal ports. Investment banks were not a success, so the State provided capital, and foreign investment was relied on as it was in Mexico. The Russians pursued education more vigorously than Mexico had. The result was an expansion of agricultural production and the creation of a heavy industrial sector but one that was not large enough to transform the economy. As in Mexico, the growth that was triggered was insufficient to tighten the labour markets, so real wages lagged. In Russia the revolution came in 1917.

In the Middle East and Asia the application of the standard model was constrained by imperialism. The first attempt to jump start industrialization was the effort of Muhammad Ali, who seized control of Egypt in 1811 and tried to turn it into a modern State. He nationalized the land and divided it into small peasant farms. He created a trade monopoly that bought crops from farmers and resold them in cities and abroad. The farmers were paid little, and the proceeds from exports were used to fund textile mills and munitions factories as well as Muhammad Ali's modern army. Many Egyptians were educated in Europe and at home, but mass education was ignored. The army seized Palestine and Syria from the Ottoman Sultan, who was Muhammad Ali's superior, Egypt being a province of the Ottoman Empire. When the Egyptians defeated the Ottomans and threatened Istanbul, the European powers intervened and forced Muhammad Ali to renounce his claims and reduce his army. In 1838, the British and the Ottoman Sultan signed the Anglo-Turkish Convention, which banned monopolies in the Ottoman Empire, thereby eliminating the fiscal basis of Muhammad Ali's modernization programme. The first experiment in State led industrial development was over.

Nationalists in India would have liked to apply the standard model but could not. Tariffs were kept low and were strictly for revenue purposes. There were no investment banks. A railway network was built in the late 19th century, but it was laid out to deploy troops for pacification and to connect agricultural districts to ports to facilitate farm exports. Building railways was a great missed opportunity. Countries like the USA, Germany, Russia, and Japan used railway building as an opportunity to expand their iron, steel, and engineering industries, but in India all of the locomotives, rolling stock, and rails were imported from Britain. Mass education was also ignored. A factory cotton spinning industry was established in Bombay and jute mills in Calcutta. These industries were important internationally but were too small to transform India as a whole.

Japan would also have liked to adopt the standard model, and its efforts were also stymied by the imperialists. Unlike India, however, Japan remained independent, which gave it more room for manoeuvre. From the 1660s, Japan had almost totally closed itself off from the rest of the world. In the early 19th century, European powers were forcing trade agreements on Asian empires along the lines of the Anglo-Turkish Convention. In the Japanese case, the Americans took the lead when Commodore Perry sailed into Yokohama harbour in 1853 demanding that the country end its isolation and allow foreign trade. The Japanese were too weak militarily to refuse, and efforts were subsequently begun to strengthen the country. The political breakthrough occurred in 1867 when the Emperor Meiji ascended the throne. The Tokugawa shogun, who had effectively ruled the country, surrendered his powers to the emperor, who assumed control. This was not just a dynastic succession but rather a virtual *coup d'état* by modernizers, who set about transforming the country. Most aspects of economic, political, and social life were overhauled.

The Meiji State aimed to force an industrial revolution by adopting the modern technology of the advanced countries. Japan pursued a variant of the standard model. First, a national market was created by abolishing internal tariffs and building a railway system.

Second, a system of universal education was established. Third, a banking system was developed although it was not until the 1920s that investment banks were successfully in operation. In the meantime, the State acted as the venture capitalist. Fourth, in 1866 the imperialist powers forced a trade treaty on Japan that limited import duties to 5 per cent. Tariffs could not be used to promote industry. Instead, the State 'picked winners' and directly subsidized firms it sought to promote. This practice developed into 'targeted industrial policy'. The tariff restrictions expired in 1894 and 1911, at which point the Japanese began using tariffs to promote industrial development as well. Japanese industrialization began with consumer goods like silk and cotton textiles in the 19th century and expanded to steel, automobiles, ships, electrical equipment, and aircraft in the early 20th.

While Japan could use subsidies and later tariffs to promote industrial development, these policy instruments in themselves did not guarantee that advanced technology would be employed. The problem was that Japanese wages were extremely low, so hand methods were often more cost effective than capital-intensive technology. Japan addressed the problem by cleverly redesigning equipment and plant operations to be less capital-intensive. A particularly simple change in the cotton industry was to operate the mills with two 11-hour shifts per day rather than only one as was the norm elsewhere. Capital costs were halved. By 1940, Japan had developed a sufficiently advanced industrial economy that it could imagine defeating the USA and Britain in the Pacific War.

The success of Japan highlights an important prerequisite for successful development, namely, a State with the capacity to set goals and the administrative competence to achieve them. In 1886, for instance, the decision was taken to create a system of universal primary education. This was an ambitious task and took decades to realize.

Administrative and technical competence were apparent before the Meiji restoration, and, indeed, that revolution might not have occurred without them. Thus, Nagasaki was unable to defend itself when HMS *Phaeton* entered the harbour in 1808 to attack the Dutch trading post because the Japanese did not possess iron cannon. The local lord appointed a team of craftsmen and savants, who translated a Dutch book describing an (outmoded) foundry in Leyden and managed to construct a copy. By 1854, they were not only casting cannon but were making replicas of modern, breech-loading Armstrong guns imported from Britain. The Meiji restoration in 1868 presupposed an advanced guard like the lord of Nagasaki committed to the modernization of the country.

Japan may have been unique in this respect. Other countries were held back by political and cultural configurations that inhibited a comparable strategy. In the 19th century, China was beset by imperialist incursions and wracked by the Taiping rebellion that was finally suppressed only by the ascendancy of regional warlords at the expense of the central government. Proposals to strengthen the country by modernizing its institutions were defeated or neutered by conservative groups whose positions were threatened by social change. They had to be swept aside before development could occur, and the overthrow of the Qing Empire in 1912 was a step in that regard. In other countries, cultural features played analogous roles. The vexed question that has obsessed Arab intellectuals since

Napoleon's invasion of Egypt in 1798 is the degree to which Islam has promoted or retarded economic development, and, if the latter, how it should be modified to facilitate progress.

Big push industrialization and the development State

In the 20th century the advantages of industrializing became even greater than previously, and, for the same reason, the challenges became more demanding. New technology requires research and development (R&D), and most R&D in the world is performed in a small number of the richest economies. Their efforts are directed to solving problems they face, so new technology is tailored to their circumstances. Over time, their wages have risen and the workforces have become more educated. The rich countries invented technology to take advantage of these characteristics of the workforce. The new technology was ever more capital intensive and raised output per worker. Eventually, the higher productivity translated into higher wages. Once an advanced economy shifted to a higher capital–labour ratio, its R&D efforts were directed to raising it even further. There was, thus, an ascending spiral of progress in which high wages led to new technology that raised output and capital per worker even further and that, in turn, led wages to go up yet again. This process continued until the late 20th century when the spiral unravelled, and real wages stagnated even as technology advanced.

Once the rich countries have moved from a low capital–labour ratio to a higher one, no country (except Japan at the outset) does further R&D to improve the low capital–labour ratio technology. Some modern technology is cost effective even in low wage countries, but not all of it. Some of it turns out to be too capital–intensive, and the lower capital–labour ratios from the past are appropriate.

From this perspective it is no surprise that the one industry in which many poor countries can compete internationally is clothing production. The key technology is the sewing machine. Treadle machines were invented around 1850, and the electric sewing machine in 1889. Nineteenth-century technology was invented when wages were much lower, and it remains the cost minimizing choice in today's poor countries. The advanced technology that poor countries need to achieve high wages and a high standard of living does not pay since their wages and living standards are so low. They are caught in a poverty trap.

To avoid this fate, governments in the 20th century undertook more interventionist policies than simply erecting tariffs. The Soviet Union was an extreme case. Under communism all firms were State owned, and profitability was not a consideration in their operations. Central planners set output targets for the economy and for each firm, and the managers were rewarded for reaching those targets irrespective of cost. When the first five-year plan started in 1928, most of the population was underemployed in agriculture, and there was a great need to build up the capital stock. Central planning proved effective towards that end, and GDP rose rapidly until the 1980s when full employment was achieved. In this period, the USSR's share of world manufacturing rose from 5 per cent to 15 per cent. To continue to grow, it was necessary to close down inefficient factories and transfer workers to higher productivity enterprises. Emphasizing output expansion and ignoring the cost side made this impossible. President Gorbachev abolished the planning apparatus and introduced market arrangements to overcome this problem, but the Soviet Union collapsed before these changes took effect. Manufacturing output has since plummeted. Turning to the 'market' was no guarantee of success.

Latin America followed a less extreme model centred on the 'development State'. The market system was retained, while the State implemented the standard model fully and augmented it with planning and socialized enterprises. Tariffs were high, infra-structure was built, State development banks supplemented private investment, and close to universal education was achieved for the first time.

These initiatives had mixed success. On the one hand, there was considerable growth, urbanization, and expansion of manufacturing capacity. On the other hand, growth was still not fast enough to catch up with the West, and industrial productivity was low. This was due to a fundamental problem: most Latin American markets were too small for firms to realize scale economies. Argentina is a case in point. In the 1960s, the minimum efficient size (MES) of an auto assembly plant was 200,000 units per year, while MES was one million units for engine and transmission plants. Only seven firms in the world—Ford, General Motors, Chrysler, Toyota, Fiat, Renault, and Volkswagen—produced more than one million cars per year. In 1959 Argentina introduced the requirement that 90 per cent of the value of cars sold in the country be made locally. However, at the time, the Argentine market was only 50,000 vehicles per year. Although the market grew to 195,000 in 1965, it was still far too small for Argentine firms to reach MES. As a result, the productivity of automobile production in Argentina was only 40 per cent of that in the leading economies. Scale problems pervaded the manufacturing sector in Latin America, and the low productivity that resulted contributed to the region's poor economic performance.

The poor performance of development States in Latin America, in India after independence in 1947, and elsewhere led many to shift their hopes for development from interventionist States to the 'free market'. This approach was epitomized by the so-called 'Washington consensus' with its trinity of stabilization, liberalization, and privatization.

Macroeconomic stabilization was supposed to increase investment, while the liberalization of trade by abolishing tariffs and quotas and the privatization of State owned firms and agencies were supposed to increase competition. Privatization and liberalization received some support from a related strand of argument that contended that competition between businesses was a source of high productivity since only efficient firms could survive in a competitive environment. State protectionism and trade impediments may reduce efficiency by sheltering inefficient firms from competition. The IMF has been particularly vigorous in restructuring the countries to which it lends along neo-liberal lines. While proponents of neo-liberalism can point to some favourable outcomes—Chile is frequently cited—the Washington consensus has been far from an unqualified success.

An underlying reason that the standard model worked less well after 1950 than it had a century earlier was the evolution of technology. In the middle of the 19th century, an efficient factory was much smaller than it is today. In the 1850s, for instance, an efficient blast furnace produced 5,000 tons per year, while the MES of a rolling mill was 15,000 tons of rails per year. The USA consumed about 800,000 tons of pig iron and 400,000 tons of rails, so there could be many efficient sized mills in the country. Even if consumers suffered from high prices, the high tariff policy did not generate an inefficient industrial structure. The situation in the second half of the 20th century was very different.

After World War II, Japan followed another variant of the development State model that was more successful and turned the country into a great manufacturing nation. Wartime destruction was total. Steel production fell from a peak of 7.7 million tons in 1943 to half a million in 1945 and rebounded to five million in 1950. At the time, MES for a steel mill was one to three million tons, and most Japanese mills were smaller with the result that steel cost 50 per cent more in Japan than in the USA. The Japanese economy was supervised by the Ministry of International Trade and Industry, and it restructured the industry to create larger mills. Japan, thus, reversed the technology policy of the Meiji era when it re-engineered foreign technology to fit Japanese factor prices. Instead, the aim became to install the most advanced technology possible and wait for the factor prices to catch up. By the 1960s the MES of a steel mill reached seven million tons, and Japan built mills of that size on greenfield sites.

Similar choices were made in automobile production, shipbuilding, electronics, and consumer durables.

Who was going to buy all of that production? A large fraction was exported to the USA. Japan benefited from two features of the post-war era. First, the USA was the world's pre-eminent manufacturing nation and felt its interests were better served by opening up foreign markets, so the high tariff policy begun in 1816 was abandoned in favour of trade liberalization. Second, Japan was particularly favoured during the Cold War. The USA regarded Japan as its outpost against communism in East Asia, and that gave Japan more scope for exporting to the USA. The export orientation of Japanese industry meant that it had to compete against highly efficient foreign producers, and those competitive pressures helped boost Japanese productivity. Access to the American market solved the scale problem for Japanese industry and underpinned its spectacular manufacturing boom. The collapse of the Rust Belt in the USA was the flip side of the East Asian Miracle.

The American market was crucial but it was not enough on its own to absorb all of Japan's manufacturing output. The domestic market had to expand as well. The employment practices of Japan's large firms played a big role. Seniority wages, lifetime employment, and company unions meant that Japanese workers earned high wages and could buy the cars and stereos that were not exported. Wages in the fringe of small firms supplying the main enterprises also rose as the labour markets tightened. There was a rapid rise in real wages in Japan between 1950 and 1990 that led to Western style prosperity and validated the technological choices that had been made.

China is in the midst of an industrial revolution right now. After the victory of the communists in the revolution of 1949, a Soviet style central planning system was created. Some basic industries were built up in the 1960s and 1970s—steel production grew from 1 million tons per year in 1950 to 32 million in 1978—but the rate of economic growth was not exceptional, and China's share of world manufacturing only grew from 2 per cent to 5 per cent between 1953 and 1980.

China's rate of economic growth increased in the 1980s, and this is conventionally attributed to the market oriented reforms introduced by Deng Xiaoping in 1978. So far as manufacturing is concerned, the first major reform was the directive to local cadres in the countryside to establish town and village enterprises (TVEs) to produce consumer goods that were sold on free markets. Chinese farmers had traditionally engaged in by-employments, and the TVE was a socialist reactivation of that capability. Since the planners had emphasized the development of heavy industry, there was a great shortage of consumer goods, and TVEs met that demand. Employment in TVEs jumped from twenty-eight to 135 million between 1978 and 1996, and their contribution to GDP rose from 6 per cent to 26 per cent. Market relations were introduced into the heavy industrial sector in the 1980s, when plan procurement targets were frozen, and increases in output were sold on markets. In 1992, the fourteenth Congress of the Communist Party resolved that a socialist market economy was the objective of reform.

With this goal in mind, Chinese industries have been remodelled in a Western manner.

Businesses are organized as corporations rather than ministerial departments. Capital investments are undertaken by the corporations rather than a planning authority, and the investments are financed by banks. There are markets in which products, materials, and labour are bought and sold. Prices vary in response to supply and demand, firms make profits or losses, and firms that cannot succeed go out of business. In some sectors foreign firms compete with Chinese firms.

It looks like capitalism—but is it really? Many of the banks and corporations are State owned, especially in priority sectors where private firms are not permitted. Five-year plans are still being written. The State Planning Commission has been replaced by the National Development and Reform Commission, which still sets targets and supervises firms. In the case of the steel industry, for instance, all of the firms are State owned and all are financed by State owned banks. There is a five-year plan for the industry, which specifies capacity, plant location, mergers, and acquisitions. To avoid having to pay high prices to foreign mining companies that supply much of the ore, the current plan calls for small firms to be eliminated, so that the industry can collude more easily, and the Chinese government is buying shares in the foreign suppliers. Between 2000 and 2013, Chinese steel output grew from 127 million tons (15 per cent of the world total) to 823 million tons (50 per cent of the world total). Almost all of the increase in world production in that period was due to expansion in China. Success was due to planning in a socialist market, not conventional capitalism. Planning, now working through the market, guided the development of other important industries as well—photovoltaics, high speed trains, and so forth.

The economy was directed by planning in other respects. Infrastructure and education (two important areas addressed in the standard model) were under direct State control. Macro-economic variables that influenced the markets were chosen with development objectives in mind. The exchange rate was intentionally undervalued. This both acted like a tariff to protect Chinese firms and an export subsidy to increase the foreign demand for their products. Current planning initiatives are aimed at increasing domestic demand for consumer goods to shift the economy away from exports and increase living standards rapidly.

Comparing China to the USSR is instructive. China has retained the parts of central planning that were effective while jettisoning those that proved counterproductive. Planning investment was the one part of the Soviet system that worked well. Guiding firms with output targets and ignoring costs was arguably productive in the 1930s but became counterproductive by the 1980s. The Chinese reforms have replaced targets and soft budget constraints with market socialism. Much investment is still planned. Combining competition with planning may have allowed China to escape the contradictions of Soviet communism.

The future of the industrial revolution

Does the industrial revolution have a future? No major country has gotten rich without industrializing. Many countries remain poor, so we must hope they will industrialize too. China is now becoming the source of cheap manufactured goods, and the industrializers of the future will have to compete against it, just as each industrializer in the past has had to compete against its predecessor—the USA against Britain; Japan against the USA; and so forth.

The spread of the industrial revolution from one poor country to the next also affects the rich countries. As a new industrial power emerges, the developed countries have found that they cannot compete against its cheap products either. As a result, the industrial sectors of rich countries have contracted, and their economies have become more service oriented.

Which country will follow China in having the next industrial revolution? Stay tuned as history unfolds …