KEYNES LECTURE IN ECONOMICS

The British Industrial Revolution in Global Perspective

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THE INDUSTRIAL REVOLUTION was a turning point in the history of the world and inaugurated two centuries of economic growth that have resulted in the high incomes enjoyed in developed countries today.[1] Technological progress is the motor of economic growth, and the Industrial Revolution is defined by famous technological breakthroughs: machinery to spin and weave cotton, the use of coal to smelt and refine iron, and the steam engine.[2] In the words of the schoolboy made famous by T. S. Ashton: 'About 1760 a wave of gadgets swept over England' (Ashton 1955: 42). The questions for today's lecture are: How can we explain the technological breakthroughs of the Industrial Revolution? And, why did the Industrial Revolution happen in Britain, rather than France, the Netherlands, or China?

These questions will be answered by developing these themes: in comparison with other countries, Britain had an unusual structure of wages and prices in the eighteenth century, and this structure of wages and prices was a major factor in explaining why the revolution happened in Britain. In addition Britain had an effective 'innovation system' based on a high

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Read at the Academy 29 October 2009.

[1] The issues in this lecture are treated at greater length and with fuller referencing in Allen (2009*a*).

[2] There has been a debate about the breadth of technological progress during the industrial revolution with Crafts (1985), and Crafts and Harley (1992, 2000) arguing that productivity growth was confined to the famous, revolutionised industries in the period 1801–31, while Temin (1997) has argued that many more industries experienced productivity growth. Whatever one believes about 1801–31, it is clear that many non-revolutionised industries experienced productivity growth between 1500 and 1850. The incentives to invent discussed in this paper applied to all industries, not just the famous ones I discuss here.

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level of human capital, the appropriate engineering capability, and a few scientific breakthroughs. These features of the British economy, which distinguish it from other countries in the world at that time, were consequences of Britain's superior trade performance and success in the European and global economies in the seventeenth and eighteenth centuries.

My interpretation is opposed to a common view that goes like this: because the inventions of the Industrial Revolution had momentous consequences, they must have been the result of momentous ideas. On the contrary, I contend that the explanation of the inventions should not be sought in great leaps of the imagination. Instead, the inventions can be better understood in terms of the hard work of research and development that was required to turn what were often banal ideas into effective technology. Hence, I take very seriously Edison's quip that invention is '1 per cent inspiration and 99 per cent perspiration'. The Industrial Revolution was primarily an engineering challenge rather than a scientific challenge.

Because so much of invention was the hard work of perfecting machinery and new products, it was an economic activity. Consequently, economic incentives were critical in explaining why that work was done and, hence, why inventions took place. Research and development became a more common business activity in the eighteenth century than it had been previously.

Many other explanations have been offered for the Industrial Revolution. Geographical dichotomies (tropics versus temperate, rain-fed versus irrigated agriculture, resource-abundant versus resource-scarce, etc.) have been invoked but face formidable counter-examples as well as the difficulty that the purpose of much technology is to overcome the burdens of nature. Culture has often been invoked (Landes 1969, Clark 2007). Europeans have usually fancied themselves more rational and hard working than the natives, and social scientists like Max Weber (1904–5) have given these views some respectability. The agricultural history of the tropics calls these thoughts into question, however, by showing that African and Asian farmers responded to economic and environmental considerations in their choice of crops and farming practices (Hopkins 1973). Less grandly, it has been claimed that cultural developments like the Scientific Revolution of the seventeenth century are responsible for the Industrial Revolution of the eighteenth. I will take up this view later.

Among economists today, 'better institutions' is the most common explanation for economic development.[3] In the case of Britain, the case

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[3] Proponents of this view include North and Weingast (1989), De Long and Schleifer (1993), LaPorta, Lopez-de-Silanes, Schleifer, Vishny (1998), Acemoglu, Johnson, and Robinson (2005).

rests on the Glorious Revolution of 1688, which assured parliamentary ascendancy, limited the power of crown, guaranteed private property, and prevented arbitrary taxation. Another line of argument is that English common law was better than French law. These explanations, of course, are restatements of eighteenth century liberal views.

If we consider the role of institutions and culture in a broader intellectual perspective, however, we notice an odd disjunction. As economists have been deciding that institutions explain everything, historians have been coming to the opposite conclusion. They have been re-evaluating many of the despotic regimes disparaged by the liberals in the eighteenth century and discovering that they functioned quite well. France, for instance, looks much better now than it did 250 years ago. Detailed comparisons show that France had lower taxes than England (Mathias and O'Brien 1976, 1978), and that French property was arguably too secure. Socially profitable irrigation projects, for instance, were not undertaken in eighteenth-century Provence because there was no legal mechanism for the compulsory purchase of land. It was only after the revolution and the ascendancy of the *Assemblée nationale* in Paris that these projects were taken forward (Rosenthal 1990). Indeed one could argue that a virtue of the English Constitution was that Parliament overrode private property with enclosure acts, turnpike acts, and canal acts. As one historian of Parliament has remarked, the great achievement of the Glorious Revolution was that the 'despotic power [that] was only available intermittently before 1688 … was always available thereafter' (Hoppit, 1996: 126). Indeed, we see it in action today.

Empire after empire has been rehabilitated. China has figured prominently in these discussions, and the so-called California School has argued that China's institutions were as good as Europe's in the eighteenth century, and, indeed, its economy was as productive (Wong 1997, Pomeranz 2000). It has also been argued that India had effective enough institutions to sustain a vast intercontinental trading empire, extensive manufacturing, large cities and realise high living standards (Parthasarathai 1998, 2001, Bayly 1989, Chaudhuri 1985). The Roman empire is another example where revisionist historians claim that imperial power created a large free trade area and sustained an extensive division of labour, advanced manufacturing, and high productivity (Bowman and Wilson 2009, Scheidel,

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For critical or contrary perspectives, see Clark (1996), Epstein (2000), Quinn (2001), Hoffman, Postel-Vinay, Rosenthal (2000), Pomeranz (2000), Mathias and O'Brien (1976, 1978), Hoffman and Norberg (1994), and Bonney (1999).

Morris, and Saller 2007, Ward-Perkins 2005). The revisionists argue that their empire created internal peace, order and good government. When these conditions were established over a wide area, interregional trade expanded and localities exploited their comparative advantage so production became spatially differentiated. The legal systems of these empires, while foreign, turn out to have been adequate to sustain this exchange and production. The result was high incomes.

In view of these findings, I take my cue from Charles Lockyer, who was an officer on the East India Company ship *Streatham*. He went to Asia to make his fortune in private trade. He was a keen student of Asian markets. He remarked:

> Arek, commonly called Bettle-nut from [Burma] would bear all Charges of Freight, Package and China Duties, and fetch fifty per Cent. Profit in Canton on a large Quantity, towards the End of Anno 1704, which is more than any other Commodity within my knowledge would do: But this is not always the same; for the Chinese, who like bees search all the coasts betwixt [India] and their own Country for Profit, have undoubtedly long since brought down the Price [in Canton] by filling their Markets with it. (Lockyer 1711, p. 72)

If the Chinese merchants were actively arbitraging markets across Asia, it shows that their legal arrangements were sufficient to support extensive trade, and they were evincing a commercial spirit as well. So it is hard to believe that China was really held back by bad institutions or a non-commercial culture. Conversely, if Britain was not blessed with better culture or better institutions, why did it make the Industrial Revolution?

The demand for technology

To make progress on this question we have to focus on the invention and adoption of technology, because technological change is the proximate cause of growth. I use a demand and supply framework. The demand for technology depended on factor prices, market size, and the imitation of novel products. Britain's unusual wage and price structure is a key for understanding the demand for technology there and why it was different to that in other countries. The supply of technology was also important, and it depended on the standard of living and accumulated knowledge, skills and inventive institutions. North-western Europe (including Britain) stands out in these regards by virtue of high levels of literacy and numeracy, but Britain was not ahead of the Netherlands or present-day Belgium. The Scientific Revolution of the seventeenth century also played a role by providing a couple of key ideas, which were the basis of important technology.

I begin with the demand for technology, which was determined by Britain's unique factor prices. In particular, wages were remarkably high in Britain, while coal and energy were cheap. This price structure created a demand for labour-saving, energy-using technology.

British wages were high in four senses. The first is comparison with wages in other countries. These comparisons require exchange rates, and I use the silver value of the currencies since silver coins were the principal medium of exchange. By the eighteenth century, British wages were higher than those almost anywhere else in the world, as Figure 1 shows.[4] This is a

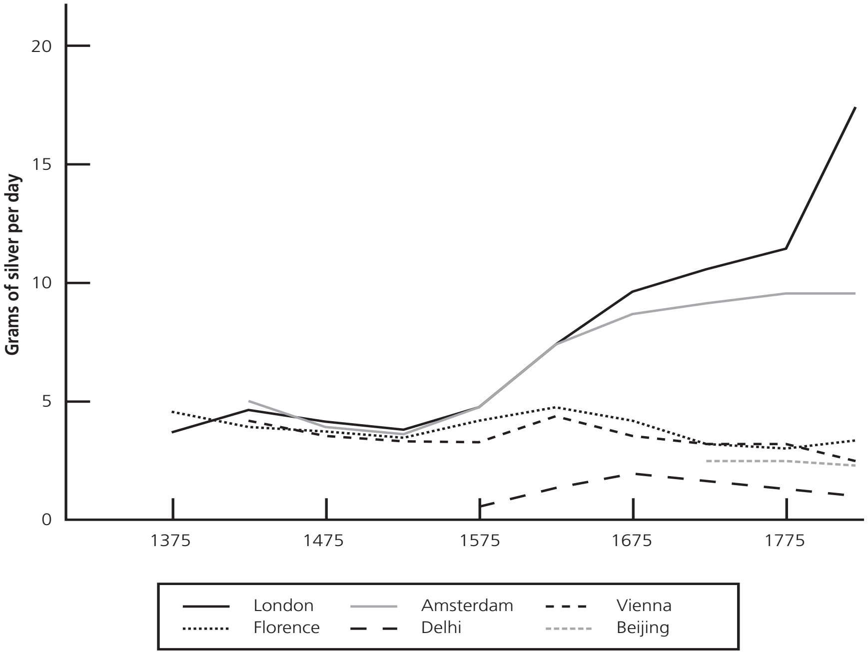

Figure 1. Labourers' wages around the world.

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[4] Figures 1–6 are based on price histories of the cities concerned. With co-authors, I have computerised these and converted the local weights and measures to metric or engineering units and the currencies to grams of silver for these comparisons. As a result, we can now compare wages and prices across Eurasia from the late Middle Ages to the twentieth century. For full sources and discussion, see Allen (2001, 2007, 2009*a*, 2009*b*) and Allen, Bassino, Ma, Moll-Murata, and van Zanden (2007).

marked change from the late fifteenth century when the wage of building labourers, for instance, was the same everywhere. Beginning in the sixteenth century, there has been a three-way split. There was little increase in wages in Central or Eastern Europe. In contrast, in Western Europe, wages rose during the price revolution (1560–1620), and they rose particularly in Britain. In the eighteenth century, British wages were higher than Asian wages, which, of course, is one of the reasons Brits went there to shop!

The second sense in which British wages were high is relative to the cost of living. Figure 2 shows the wage rate deflated by an international, intertemporal consumer price index. I will explain in a moment how it was calculated. It is a commonplace today that the standard of living is more or less the same everywhere in Western Europe, so we can ask: when in the past (if ever) was that last true? The answer is the end of the fifteenth century. At that time real wage differences between European cities were small. Since then, they have diverged. Real wages in North-western Europe remained more or less constant from the end of the Middle Ages until the 1870s. (It is remarkable that the Industrial Revolution passes through

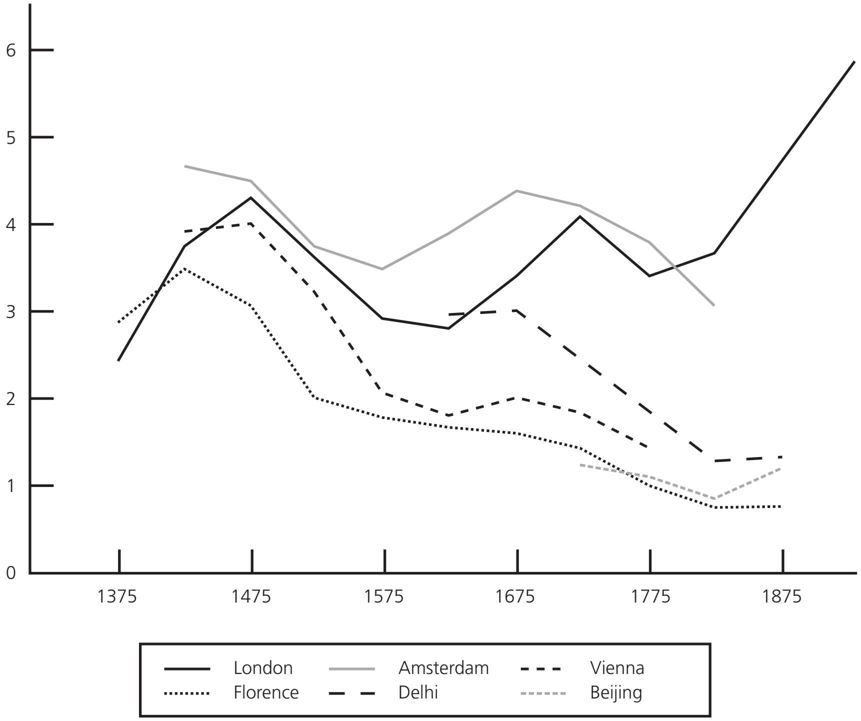

Figure 2. The subsistence ratio for labourers.

these time series without a trace!) The real wage, however, in Central and Southern Europe dropped. As a result, there was a great divergence of living standards within Europe before the Industrial Revolution. Also, living standards in the Asian cities were on a par with those of Southern and Central Europe in the eighteenth century—not with England or the Low Countries. A rich North and a poor South was not a consequence of the Industrial Revolution but preceded it. Indeed, my argument is that the Great Divergence caused the Industrial Revolution.

These figures have a further interpretation because of the way they have been scaled. Most of the Central and Eastern European real wage series as well as the Asian series end up with a value of about one in the eighteenth century. What that means is that a labourer who worked full-year, full-time earned just enough money to support a family at a bare-bones standard of living. This standard was one in which an adult male consumed 1940 calories per day. The calories came mainly from boiled grains and beans. The diet was quasi-vegetarian with very little flesh and some butter or oil. Non-food items included a few candles, soap, and three metres of cloth for clothing. There was a 5 per cent allowance for house rent. Table 1 shows the spending pattern as it was specified for North-western Europe where oatmeal was the cheapest source of calories. The diet was modified for other parts of the world to use the cheapest available carbohydrate, that is polenta in Florence, sorghum in Beijing, millet chipatis in Delhi, rice in Madras, maize in Mexico. This kind of bare-bones diet was common in most of Asia and Southern and Central Europe. It was all that labourers could afford.

Table 1. The annual subsistence spending pattern of a man in North-western Europe

	Quantity per year	Calories per day	Grams of protein per day
Foods			
Oats	155 kilograms	1657	72
Beans	20 kilograms	187	14
Meat	5 kilograms	34	3
Butter	3 kilograms	60	0
Total		1938	89
Non-foods			
Soap	1.3 kilograms		
Cotton	3.0 metres		
Candles	1.3 kilograms		
Lamp oil	1.3 litres		
Fuel	2.0 million BTU		

Source: Allen (2009*a*, p. 37), which also gives examples of subsistence based on maize, millet, and rice. The basket in the table is the consumption pattern of a man. The annual cost of maintaining a family is taken to be the cost of three of these baskets plus 5% for rent.

As Figure 2 shows, labourers in North-western Europe earned four times bare-bones subsistence in the eighteenth century. They did not eat four times as much oatmeal as shown in Table 1. Instead, they upgraded the quality of their food to bread, beer and beef. They also had a bit of purchasing power left over to buy the Asian commodities like tea and the manufactured goods of the consumer revolution in the eighteenth century. That is why the consumer revolution happened in North-western Europe in the eighteenth century and why it was mainly confined to North-western Europe insofar as it affected the working class.

A third sense in which British wages were high is relative to the cost of capital goods, and this is critical for the choice of technology and the process of invention. Figure 3 shows the builder's wage rate relative to the user cost of capital based on the prices of wood, iron, non-ferrous metal, and bricks and an interest rate and depreciation rate. In Strasbourg, Vienna, and southern England there was not much difference in the ratio of the wage rate to the price of capital early in the seventeenth century, but by the eighteenth century a big differential had emerged. Labour was much more

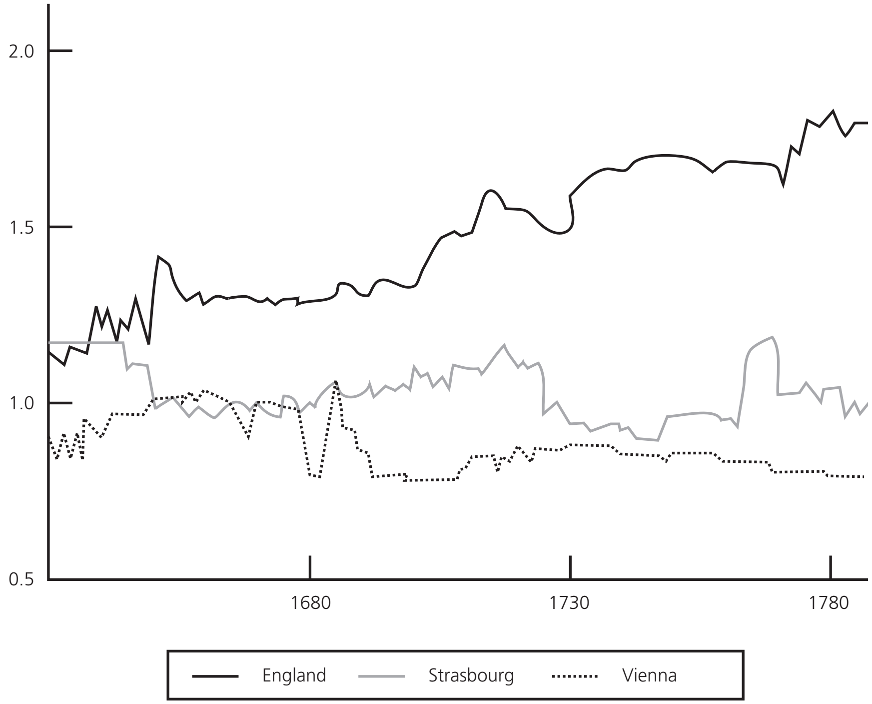

Figure 3. Wages relative to price of capital.

expensive relative to capital in Britain, and that difference gave British businesses a strong incentive to use capital intensive technologies and British inventors an incentive to invent them.

The fourth sense in which British wages were high was relative to the price of energy. Figure 4 shows energy prices in different cities early in the eighteenth century. In this figure the prices of the various fuels (coal in London, peat in Amsterdam, etc.) are reduced to their energy content measured in British Thermal Units (BTUs). Newcastle had the cheapest energy since coal was mined there. Beijing had the most expensive energy, Paris was almost as expensive, while Amsterdam and London were in the middle. The difference between the price in London and Newcastle reflects the transportation costs incurred in shipping the coal down the coast from Newcastle to London. Coal reached Amsterdam at almost the same price as it was available in London because it was just as cheap—or as expensive—to send a boat from Newcastle to Amsterdam as to London.

The low cost of energy on the British coalfields meant that the wage rate relative to the price of energy was very high in Newcastle (Fig. 5). High British wages also contributed to this result, but cheap coal was the decisive factor.

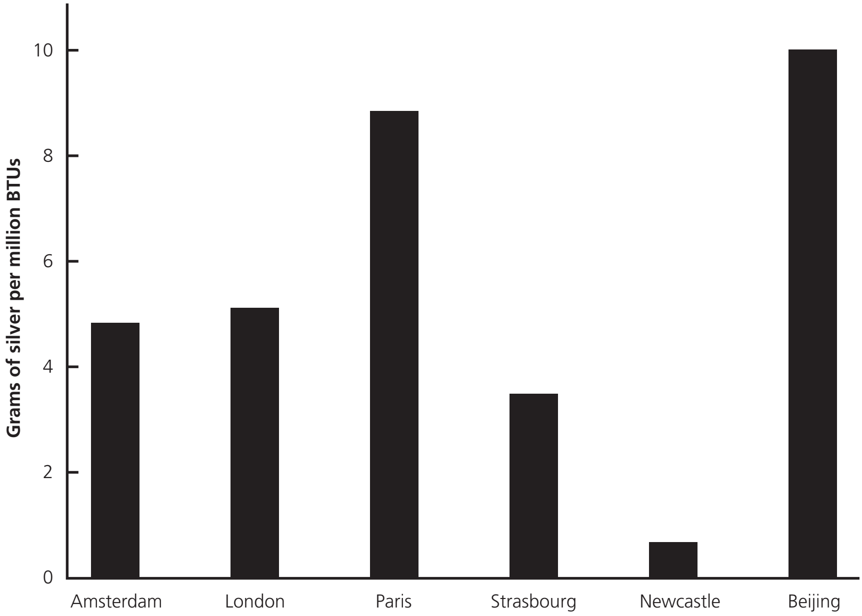

Figure 4. The price of energy in the early 1700s.

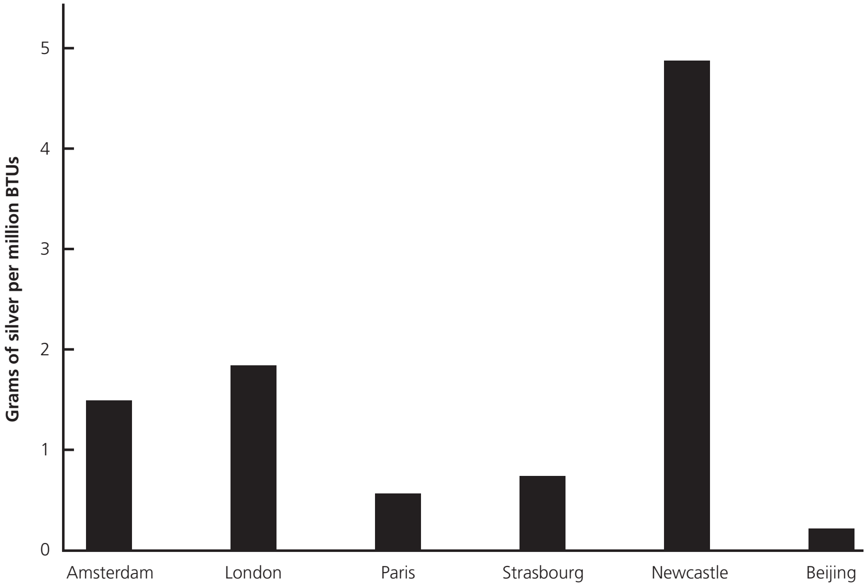

Figure 5. The price of labour relative to energy, early 1700s.

Contemporaries were aware of these relative prices. An interesting case in point is the production of plate glass, which was an industry in which the French were technological leaders. They had a major production centre at Saint Gobain, and the British imported the French technology to Ravenshead in the late eighteenth century. This was not just theft. There was cooperation with the French works. Delaunay Deslandes, who was the director of Saint Gobain, thought this was a quixotic thing for the British to do because he could not imagine how they could compete against the French. As he said,

> Given the manner in which the English and French lived … they could never make plate [glass] which could enter into competition with ours for the price. Our Frenchmen eat soup with a little butter and vegetables. They scarcely ever eat meat. They sometimes drink a little cider but more commonly water. Your Englishmen eat meat, and a great deal of it, and they drink beer continually in such a fashion that an Englishman spends three times more than a Frenchman.[5]

Deslandes was describing the high cost diet that English workers could afford with their high wages in the eighteenth century. If the British glass works were going to have to pay these high wages how could they compete

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[5] Quoted by Harris (1975, p. 67, n. 42).

with low-wage French labour? The answer is that English coal cut fuel costs to one-sixth of the French level. Cheap coal sustained the high-wage economy.

High wages and cheap energy were the distinctive features of the British economy during the Industrial Revolution. Where did this price structure come from? It was a result of Britain's foreign trade boom in the seventeenth and eighteenth century (Allen 2003, 2009*a*, pp. 106–31). The boom began in the seventeenth century with the new draperies and was consolidated with the creation of a world empire in the eighteenth. The trade boom pushed the urbanisation rate from 7 per cent in 1500 to 29 per cent in 1800, which was one of the highest percentages in Europe. The growth of London accounts for much of this urbanisation. Its population rose from about 50,000 in 1500 to 200,000 in 1600, to half a million in 1700, and reached one million in 1800. The growth of the city was driven by the growth in the volume of trade though the port. The resulting tight labour markets were the proximate cause of the high wages. They were sustained eventually by the cheap energy.

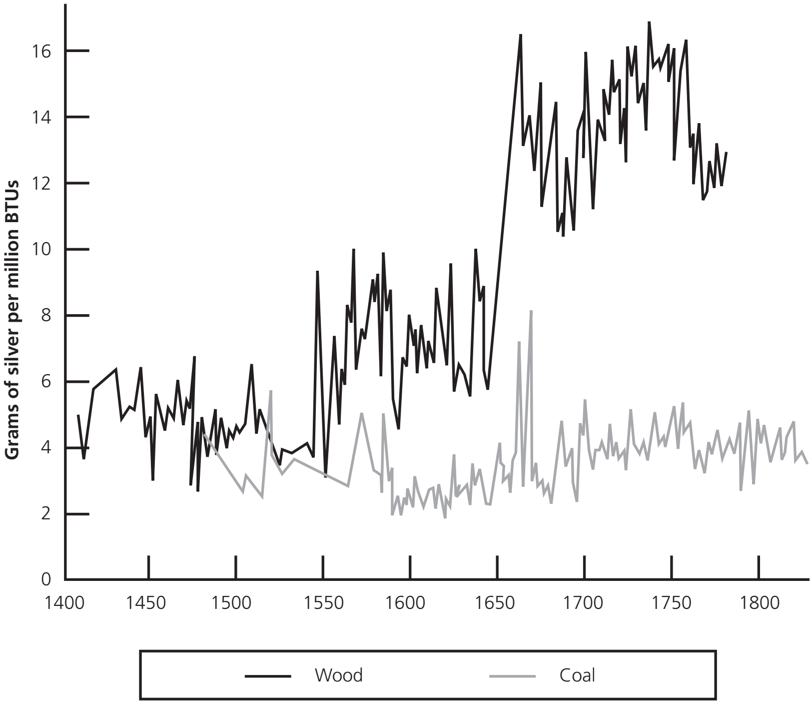

Figure 6. The real prices of wood and coal in London.

As London grew, the demand for fuel for industrial purposes and domestic heating increased as well. At the outset, most of the fuel was either firewood or charcoal, and this had to be shipped over greater and greater distances at greater and greater cost. Consequently, the price of fuel rose as the city expanded. Eventually, the prices of wood and charcoal rose high enough to make it profitable to use coal. Figure 6 charts this transition. The figure shows the real price of fuel, that is the price per BTU deflated by a consumer price index. At the end of the Middle Ages the prices per BTU of wood fuels and coal were similar. Under those circumstances, coal was only used to burn lime and for blacksmithing, uses in which it was regarded as superior to wood. In all other uses, wood was preferred. For heating, cooking, and most industrial processes, coal was the inferior fuel since it contained sulphur, which burnt with a foul smell and contaminated industrial processes (Nef 1932, Hatcher 1993).

The price of wood and charcoal rose in the sixteenth century and, by 1580, the price of charcoal per unit of energy was twice the price of coal. That differential was large enough to induce people to redesign their technologies, so that they could use the cheaper fuel. Indeed that is when the coal trade took off.

Technology responded to factor prices

High British wages and cheap coal underpinned the Industrial Revolution by creating a demand for technology that substituted capital and energy for labour. In Asia and much of Europe, low wages and dear energy had the opposite effect. Silk weaving is one example. The English industry began when the Lombe brothers built a mill in Derby in 1715–19. It was expensive to erect and was powered by a water wheel, which was a capital-intensive system. What about the situation in Asia? The Tsukiji silk mill was built in Japan *c.*1870. It used European-style machinery, but it was re-engineered to be more labour-intensive in accord with Japanese factor proportions. It did not have a water wheel. Instead it was powered by a man turning a crank—a labour-intensive process, indeed! In England where labour was very expensive and capital was relatively cheap, a capital-intensive method was used, whereas in Japan, where labour was cheap, a labour-intensive method was preferred. Factor prices influenced the choice of technique at the opposite ends of Eurasia.

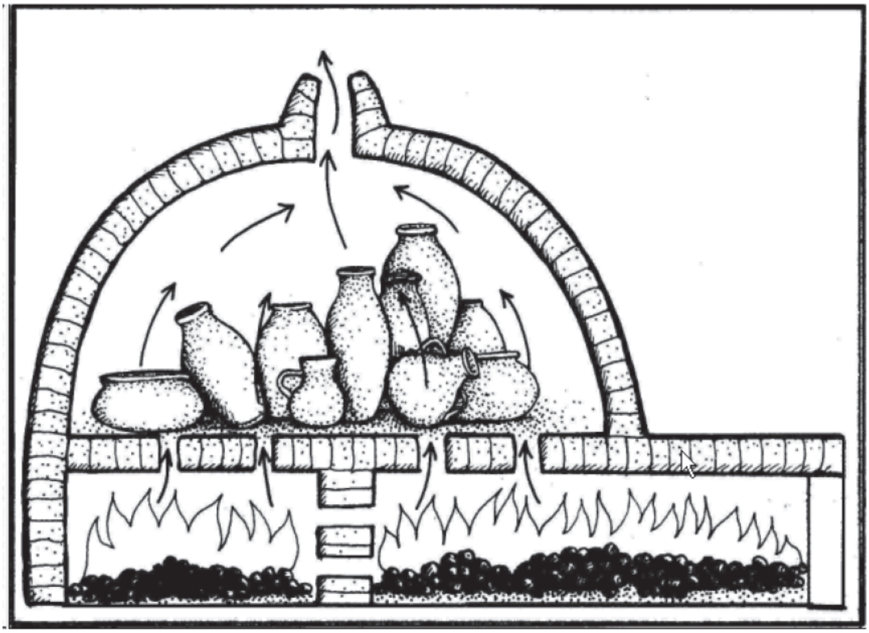

Figure 7. An English-style pottery kiln.

Another example that relates to energy is pottery production in China and England. Pottery kilns in England were built to economise on capital and were profligate in their use of energy. Figure 7 shows an English-style kiln. It had a coal fire in the bottom. The heat rose, enveloped the pots, and then vented out of the furnace through the 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 and employed lots of labour to preserve energy. Figure 8 shows a fire 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 the bottom into the next chamber. 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 factor prices. In this case, expensive fuel in China led to the substitution of capital for energy, in contrast to English design.

The same considerations governed invention in Europe. Nail making is a prosaic example. One of the steps in making nails is putting the head

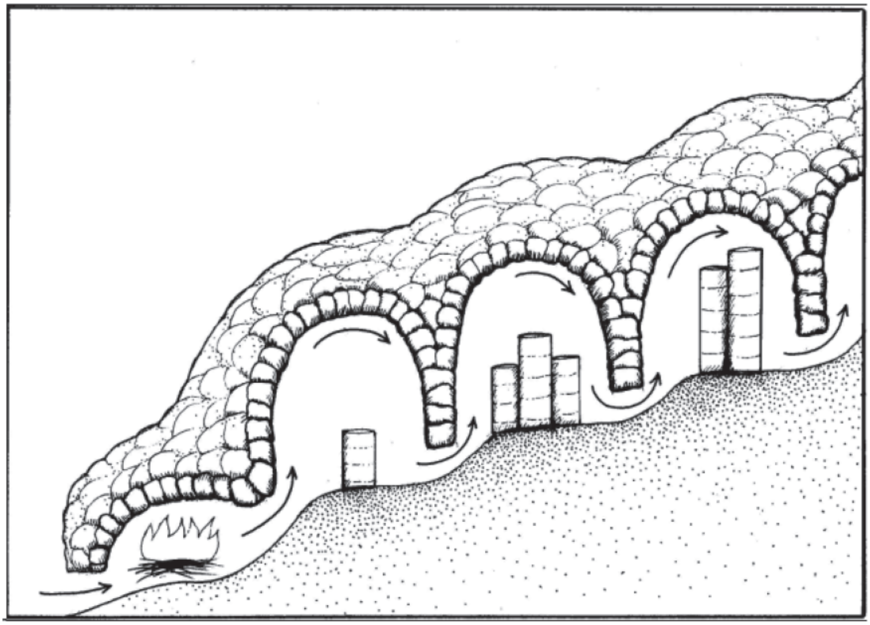

Figure 8. A Chinese-style pottery kiln.

on the nail. In Britain at the end of the seventeenth century a machine was developed to mechanise that process. It was called the oliver. It was a device like a sledgehammer. The shaft was hinged at the base. The head of the 'hammer' had a hole in which a dye was placed to shape the head of the nail. The hammer was raised with a foot pedal and then released so the head would drop on a nail and shape it. In contrast, in French nail shops there was no oliver. Again we have a situation where the low-wage country, France, was using the more labour-intensive process.

The two stages of technological evolution

The history of technology is a two-stage process. So far I have been discussing the first stage. It includes the famous macro-inventions of the Industrial Revolution—the spinning machinery, coke blast furnaces, weaving machines, and steam engines. These involved substantial changes in input proportions. They radically increased the amount of coal that was used, for instance, or increased capital relative to labour. They turn out to have been profitable at British input prices because they used intensively things that were cheap in Britain. At the outset, however, they barely covered costs, even in Britain. Despite the fact that a hundred years later these machines revolutionised the world, in the beginning they just barely paid their way.

The second stage of the history of technology comprises the improvement of the revolutionary machines. This is the phase of micro-inventions. Engineers, owners, and operators studied the machines to improve them. The objective was to reduce costs, and, in the event, all inputs were saved, irrespective of whether they were abundant or scarce. Eventually a tipping point was reached when it became profitable to use these technologies (in their improved form) outside Britain. That is when the Industrial Revolution spread around the world.

We can illustrate the two stages with isoquant diagrams. In the mid-eighteenth century, the only way to make coarse cotton yarn was with a spinning wheel. In Figure 9, this is represented by a single point corresponding to the labour of one woman and the cost of a wheel. Together they produced one pound of yarn per day. Two isocost lines are drawn—one for a high-wage economy and one for a low-wage economy. Both

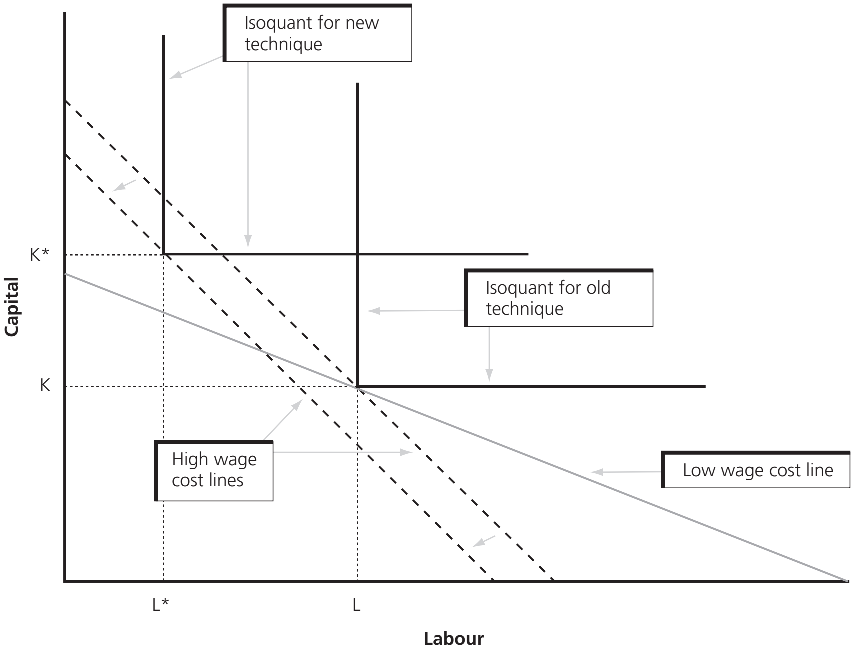

Figure 9. Isoquants for spinning yarn: mid-eighteenth century.

touch the single point of the isoquant since that represents the only way to make cotton whatever your factor prices.

The spinning jenny is represented on the diagram with another point with more capital and less labour. With a jenny, a woman could spin one pound of coarse yarn in a couple of hours rather than a full day, but the jenny cost considerably more than the wheel. As the points are drawn, it would have been profitable to adopt the jenny in the high-wage economy, but it would have raised costs in the low-wage economy, so it would not have been used there. In 1787, over 20,000 jennies were installed in Britain but only 900 were installed in France in 1790, and most of those were in large state-assisted factories rather than in women's cottages as in England (Aspin and Chapman 1964, p. 49, Wadsworth and Mann 1931, pp. 195–9, 503–4). This diagram illustrates the important point that biased technical changes do not cut costs in the same proportion everywhere. The reduction depends on factor prices, so biased technical change favours some parts of the world over others. The technologies that were invented in Britain raised labour productivity and covered their costs only when they were used under the conditions of Britain in the eighteenth century.

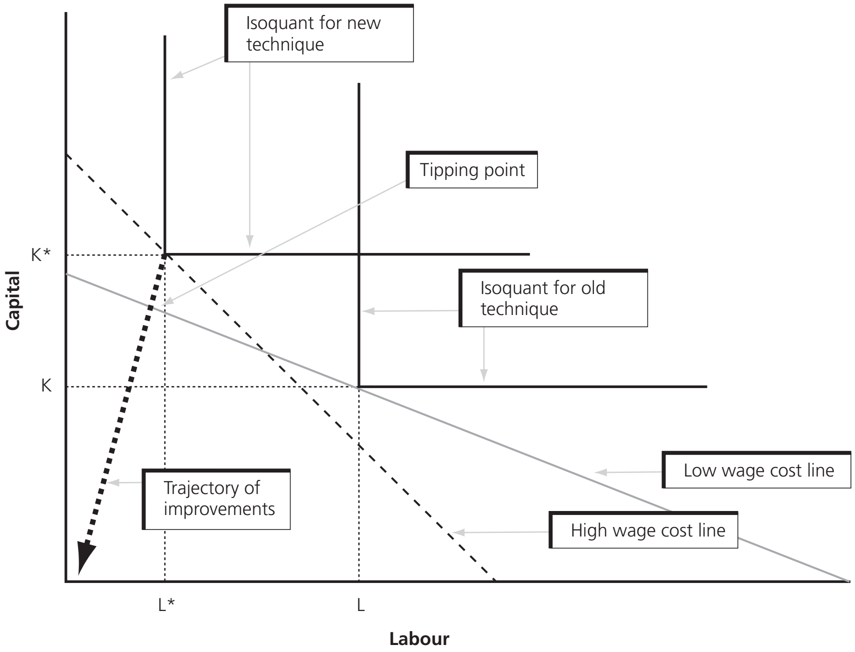

Figure 10. Isoquants for spinning yarn after technological improvements.

Table 2. Adult literacy, 1500–1800: percentage of the adult population that could sign its name.

	1500	1800
England	6	53
Netherlands	10	68
Belgium	10	49
Germany	6	35
France	7	37
Austria/Hungary	6	21
Poland	6	21
Italy	9	22
Spain	9	20

Source: Allen (2009a, p. 53).

The second stage of technological development proceeded in this way: British engineers learned how to improve the spinning jenny as they used it and studied it. The mule was one of the first spin-offs, and improved versions of it were used in many countries in the middle of the nineteenth century. This trajectory of improvement is represented by the arrow towards the origin in Figure 10. As the technology was improved, labour and capital were saved. By installing the first cotton spinning machines, Britain became the world's technological leader, and the subsequent improvements extended Britain's lead. Historians as well as contemporaries have debated why France was not keeping up. Was it bad entrepreneurs or an engineering culture that was too theoretical? In fact, it was neither. At the end of the eighteenth century, it did not pay to spin with machines in France. Eventually, however, enough inputs were saved so that the cost of producing cotton with the improved process dropped below the cost of spinning with a wheel *even in the low-wage country*—like France. That juncture was the tipping point when the industrial revolution shifted abroad. Indeed, there was a great leap forward as the foreigners adopted the technology in its most advanced form. That, of course, was the only form that paid, given their lower wages.

The supply of technology

Thus far, my argument has been about the demand for technology. There was also a supply-side story that is prompted by the observation that not all high-wage economies have invented labour-saving machinery. The late Middle Ages had a high-wage economy, but it did not lead to an Industrial

Revolution. Why not? The answer has two parts. First, commerce and urbanisation were more widespread in the eighteenth century than they had been in the Middle Ages, and trade and cities led to high levels of human capital. Second, the Scientific Revolution of the seventeenth century included scientific discoveries that led to two important technologies.

First, with respect to human capital, Table 2 shows estimates of literacy rates in different countries (defined on modern borders) in 1500 and 1800. These estimates are based on the proportions of people who could sign their name. In 1500, literacy was low everywhere. By 1800 it was higher everywhere and especially in North-western Europe. One explanation for the rise in literacy is the Protestant Reformation. This is doubtful, however, since the highly literate parts of Europe in 1800 included Belgium and North-eastern France, which were Catholic countries. The driving force behind literacy was really urbanisation and the expansion of commercial society. Literacy was valuable in trade and cities, and that value led parents to pay for schooling for their children. So far as we can tell from phenomena like age heaping, numeracy also increased in the early modern period in North-western Europe (Thomas 1987, A'Hearn, Baten, and Crayen 2009). Few people studied arithmetic for fun; the acquisition of numerical skill was entirely driven by economic value.

Second, the Scientific Revolution was another important difference between the Middle Ages and the eighteenth century. Some historians have emphasised its impact on the culture at large, but I concentrate on specific connections between scientific discoveries and technological advances. Two discoveries were bases for two General Purpose Technologies (GPTs). The concept of General Purpose Technology was inspired by the computer and refers to technologies that can be adapted to many sectors of the economy. In the Industrial Revolution, the GPTs were steam power and 'clockwork', or gearing. Both had connections to the Scientific Revolution, although in the case of gearing the relationship was a distant one. Both technologies required Research and Development (R&D) projects to make them effective in the various settings. The R&D projects were more profitable in Britain than elsewhere, which is why the Industrial Revolution was invented in Britain, as I will show you.

The steam engine was an important application of knowledge discovered by seventeenth-century scientists.[6] The science began with Galileo,

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[6] Standard works on the history of the steam engine include Farey (1827), Dickinson (1939, 1958), Forbes (1958), Hills (1970, pp. 134–207, 1989), Nuvolari (2004), and von Tunzelmann (1978).

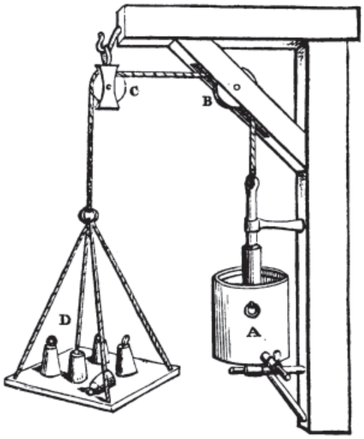

Figure 11. von Guericke's apparatus.

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 noticed that suction pumps would not lift water more than about thirty feet. He put his secretary Evangelista Torricelli to work on this project. Torricelli invented the mercury barometer and weighed the atmosphere. In 1672, von Guericke of Magdebourg designed the apparatus shown in Figure 11, also to weigh the atmosphere. The cylinder, which is labelled A, contained a piston from which ropes went over the pulleys to hold the platform on which he 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 Guerick experiment shown in Figure 11 is similar to the first successful steam engine invented by Newcomen in 1712 (Fig. 12). Newcomen's engine has the cylinder on the right (B) with a piston (D) in it. Instead of the pulleys, there is a balance beam (HF) and, instead of the weights on the left, there is a pump (I) for lifting water out of a mine. By filling the cylinder with steam from the boiler (A) and then condensing it with a squirt of cold water (B), the atmosphere would push the piston down and raise the pump. When the vacuum was relieved, the weights (K) above the pump pulled the left end of the beam down, steam was allowed to enter the cylinder, and the cycle was repeated. Newcomen had found

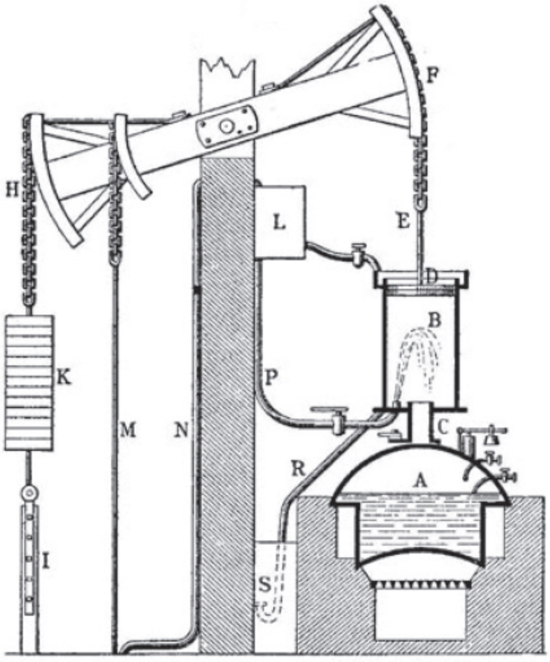

Figure 12. Newcomen's steam engine.

a way to raise water—and make money—from the weight of the atmosphere.

The science underlying the steam engine was pan-European (the leading scientists were Italians, Germans, and French), but the 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 eighteenth century, observed that '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' (Desaguliers 1744, II, pp. 464–5). The reason it was profitable to develop the Newcomen engine in Britain was because there were coal mines to be drained.

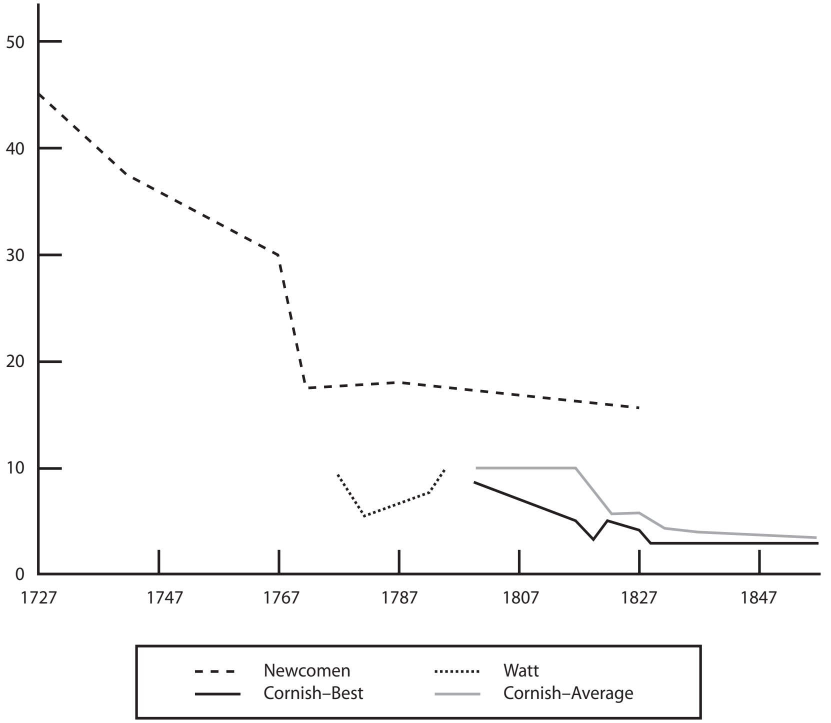

Figure 13. Coal consumption in pumping engines (lbs per HP-hour).

Newcomen's engine was the macro-invention that marked the first phase of this technological trajectory. The second phase consisted of the perfection of the engine and involved many of the most famous engineers of the Industrial Revolution. This phase involved saving all inputs and, in particular, coal, which was cheap in Britain. Figure 13 shows the evolution of fuel consumption in pumping engines from an early Newcomen engine in 1727 to the highly efficient engines of the mid-nineteenth century. It includes the contributions of John Smeaton, James Watt, Richard Trevithick, Arthur Woolf, and the many engineers who improved Cornish engines. Fuel consumption dropped from 44 pounds of coal per horsepower-hour in 1727 to 3 pounds in 1847. This improvement was a triumph for British engineering, and it also destroyed the country's competitive advantage by turning the steam engine, which had mainly benefited Britain in the early eighteenth century, into a technology that could be used anywhere in the world. Once the coal consumption was reduced to 3 pounds per horsepower-hour, the price of coal became irrelevant to the engine's commercial application.

British engineers had invented the 'appropriate technology' for the rest of the world.

Clockwork was the second General Purpose Technology in the Industrial Revolution.[7] Clockwork refers to the use of gears to control and distribute power in machinery. Gears had been used for a long time. Medieval gears, however, were usually large, wooden, and crude. By the eighteenth century, gears had become small, metallic, and precise. The improvement in gears goes back to the invention of the pendulum clock by Christiaan Huygens in 1656. He was, of course, a world-class scientist and mathematician, and he was working on a world-class scientific problem. This was the measurement of longitude, and it had come to the fore with global navigation. The solution was easy if you knew the time difference between your location and Greenwich, and that was simple if you carried a time piece set to Greenwich Mean Time. The problem was designing an accurate clock or watch. Huygens realised that he could improve the accuracy of a clock by adding a pendulum. The result was a better clock, and the clock industry expanded considerably. However, Huygens' clock was not a satisfactory solution to the longitude problem since a pendulum clock did not keep good time on a ship pitching at sea. Huygens did not give up, however. He applied himself to improving the accuracy of watches and invented the coiled spring. This greatly improved their accuracy, although again not enough to determine longitude with sufficient precision. Nonetheless, the watch industry grew enormously since the more accurate watches were in demand. Attention was directed towards improving the production of gears. In 1656, each gear had to be laid out by hand on a sheet of brass with a protractor. The teeth were marked and then sawn out individually with a file. In the second half of the seventeenth century, machines were developed that did the laying out and cutting automatically with the result that, by the eighteenth century, gears had become not only cheaper but also standardised and more accurate.

Gears had uses besides watches. Early applications included automata—clockwork toys, some of which were very elaborate. One of the most famous was the duck made by the great French engineer Vaucanson. The duck walked across the floor eating and pooping. It was a great hit at Versailles; according to Voltaire, 'Without Vaucanson's duck, you would have nothing to remind you of the glory of France.' Of course, if you could control the movement of a toy duck with gears, perhaps you could do something useful like spin yarn or weave cloth. Edmund Cartwright,

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[7] On the history of clocks and watches, see Weiss (1982) and Landes (2000).

the inventor of the power loom, was inspired in part by automata, and the distribution of power to the rollers in Arkwright's water frame was called 'the clock work' since it used gears like a watch or clock. Indeed, Arkwright hired clockmakers over a five-year period to design it.

The possibility of using gears to design machinery was greatest where gears were made. As it happens, Britain had the largest watchmaking industry in the world since the high-wage economy sustained a high demand for watches. While final assembly was done in London, the watch movements themselves were outsourced to southern Lancashire. Preston and Warrington had large industries making gears and supporting industries that made the tooling to make the gears. The watchmakers and the toolmakers provided the 'high tech' inputs to produce textile machinery in the 1780s and 1790s. Britain's success in 'practical skills and engineering', which has often been identified as a cause of her industrial success, was the result of her earlier success in watchmaking.

The economic basis of the Industrial Revolution

Both steam power and clockwork were rooted in scientific discovery; nonetheless, they illustrate the importance of incentives in explaining eighteenth-century inventions. This lecture has advanced an economic explanation of the Industrial Revolution that involves three key ideas relating to incentives:

- Engineering problems were the crux of invention;
- The engineering problems were addressed in response to economic incentives resulting from Britain's high wages and cheap energy; and
- *The famous inventions of the Industrial Revolution were made in Britain because it paid to invent them in Britain, not because the British were more practical, more enterprising, or better governed.*

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