Allen (2009)

6 Why was the Industrial Revolution British?

> Invention is 1% inspiration and 99% Perspiration.
>
> Thomas Edison

The Industrial Revolution was one of the great, transformative events of world history. Part I explored the high wage, cheap energy environment from which it emerged. Part II will show how and why that environment caused the Industrial Revolution. But what was the Industrial Revolution? Its essential characteristic was technological innovation. In the words of Ashton's famous schoolboy: 'About 1760 a wave of gadgets swept over England.'[1] Some are well known (the steam engine, the spinning jenny, the water frame and coke smelting), and others less so (devices to lay out and cut the gears of watches, and foot-powered trip hammers to stamp the heads on nails).[2] In the remainder of this book, I concentrate on the famous inventions because they unleashed trajectories of technological advance that drove the economy forward. If we can explain the breakthroughs that started these sequences of progress, we can explain the Industrial Revolution. The basic principles have broader application, however, and governed minor inventions as well. In the remainder of this book, I tackle the question of why the steam engine, mechanical spinning and coke smelting were invented in Britain, in the eighteenth century.

The famous inventions had a life course, and I shall tell their biographies, for they give the Industrial Revolution a natural unity. The inventions began with a conception and were born through difficult labour. In their youth, they were decidedly British in their biases. As

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[1] Ashton (1955, p. 42).

[2] There has been a lively debate about the importance of productivity growth in the famous 'revolutionized' industries versus productivity growth in industries where inventions were less dramatic. See McCloskey (1981), Temin (1997, 2000), Harley (1999), Crafts and Harley (2000, 2002), Berg and Hudson (1992, 1994), Bruland (2004).

they matured, these biases wore away, and the inventions were adapted to any circumstances. At that point, the Industrial Revolution diffused to the continent, to North America, and then to the rest of the world. This lifespan took a century and a half, and it sets the natural limits of the Industrial Revolution. I shall tell the history of the Industrial Revolution in two stages: first, the birth and youth of the great inventions when they were useful in Britain but nowhere else, and, secondly, their maturation into globally useful technologies that spread from Britain to other countries.

My analysis is based on two distinctions. The first is between macro-inventions and micro-inventions.[3] Newcomen's steam engine and Hargreaves' spinning jenny, for instance, were macro-inventions. They set in train long trajectories of advance that resulted in great increases in productivity. Fundamentally for my analysis, they also radically changed factor proportions, substituting energy and capital for labour. For this reason, the macro-inventions of the Industrial Revolution were only cost-effective in Britain. Micro-inventions, on the other hand, refer to all of the improvements in the trajectory of advance that elaborated macro-inventions and realized their possibilities. Economies were made across the board – in the use of inputs with which Britain was abundantly endowed (e.g. coal) as well as in the use of inputs that were scarce in Britain (e.g. labour). As a result, the stream of micro-inventions made steam engines, cotton mills and coke blast furnaces cost-effective in more and more countries and eventually spread the Industrial Revolution around the world.

The second distinction concerns the nature of invention itself, namely, Edison's observation that 'invention was 1% inspiration and 99% perspiration'. Invention involved both leaps of imagination or scientific discovery (inspiration) and research and development (perspiration). Usually, 'inspiration' is emphasized,[4] but both need to be explained, and Edison's weighting suggests that we should concentrate on research and development. I will consider both inspiration and perspiration, but I will follow Edison's lead and concentrate more on

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[3] The distinction is Mokyr's (1990, p. 13), although my understanding is different. Mokyr (1991), however, does discuss the relationship between macro- and micro-inventions in a similar way to that used here. The distinction between the two types of invention was anticipated by Rosenberg (1982, pp. 62–70).

[4] MacLeod (2007) deconstructs the view that the inventors of the Industrial Revolution were inspired geniuses.

the latter than has been customary. This perspective is rewarded with a deeper understanding of why the Industrial Revolution happened when and where it did.

I analyze the search for better methods in terms of the demand and supply of new technology. Britain's success in the early modern global economy gave her expensive labour and cheap energy. These prices affected the *demand* for technology by giving British businesses an exceptional incentive to invent technology that substituted capital and energy for labour. The high real wage also stimulated product innovation since it meant that Britain had a broader mass market for 'luxury' consumer goods including imports from east Asia.

This view of Britain and British technology has an important precedent, namely, Habakkuk's (1962) explanation of American technology in the nineteenth century. The United States emerged as the world's leading economic power after 1870, and the basis of American success was the remarkable degree to which its technology increased the productivity of labour. Habakkuk attributed the labour-saving bias of American inventions to the high wages of the American economy, which, in turn, were due to the abundance of land and natural resources in north America.[5] Eighteenth-century Britain was the prequel to nineteenth-century America.[6] In Britain, cheap energy underpinned a high wage economy that induced the invention of labour-saving technology, just as abundant land led to high wages and the labour-saving bias of American inventions in the nineteenth century.

High wages increased the *supply* of British technology as well as the demand for it. High wages meant that the population at large was better placed to buy education and training than their counterparts elsewhere in the world. The resulting high rates of literacy and numeracy contributed to invention and innovation.

The supply of technology was also affected by other developments. Jacob (1997), Stewart (2004) and Mokyr (1993, 2002) have emphasized the importance of Newtonian science, the Enlightenment and

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[5] Hahn and Matthews (1964, pp. 852–3) summarize standard objections to the Habakkuk view, including the observation that profit-maximizing firms are indifferent between saving capital or labour. See also Salter (1960) on this point. My emphasis on the cost of R&D and the expectations about the bias of the resulting technology are meant to address this.

[6] Fremdling (2004, pp. 168–9) entertains this possibility, as does Mokyr (1993, pp. 87–9), who also raises many objections to it.

genius in providing knowledge for technologists to exploit, habits of mind that enhanced research, networks of communication that disseminated ideas, and sparks of creativity that led to breakthroughs that would not have been achieved by ordinary research and development. Mokyr's influential interpretation conceptualizes these elements as the Industrial Enlightenment. These developments would have boosted the rate of invention at any level of wages, prices and human capital. That is also their weakness. The Scientific Revolution and the Industrial Enlightenment were Europe-wide phenomena that do not distinguish Britain from the continent. That is appropriate in some contexts: France was in the lead in many industries with new techniques to her credit in paper, clocks, glass and textiles, for instance (Hilaire-Pérez 2000). Any theory that explains British success by positing a British genius for invention is immediately suspect. Instead, we must explain why Britain invented the technologies she did. The solution turns on the demand for technology and the price structure of the British economy.

Britain: a high wage, cheap energy economy

In Chapter 2, we saw that British wages were very high by international standards, both at the exchange rate and in terms of the standard of living that they bought. In Chapter 4, we saw that British energy prices were exceptionally low, especially near the coal fields of northern and western Britain. These are important features of the economy, but they are not the critical ones in so far as the demand for technology is concerned. The demand for technology depended on the price of labour relative to the prices of other inputs in production, i.e. the price of labour relative to the prices of capital and energy.

The price of labour relative to capital is shown in Figure 6.1, which plots the daily wage of a building labourer divided by an index of the rental price of capital in the English midlands, Strasbourg and Vienna. The rental price of capital is an average of the price indices for iron, non-ferrous metals, wood and brick, multiplied by an interest rate plus a depreciation rate. Strasbourg and Vienna were chosen since there are long series of wages and prices for those cities, and their data look comparable to those of most of Europe apart from the Low Countries. The series are 'PPP adjusted' so that we can compare across space as well as over time.

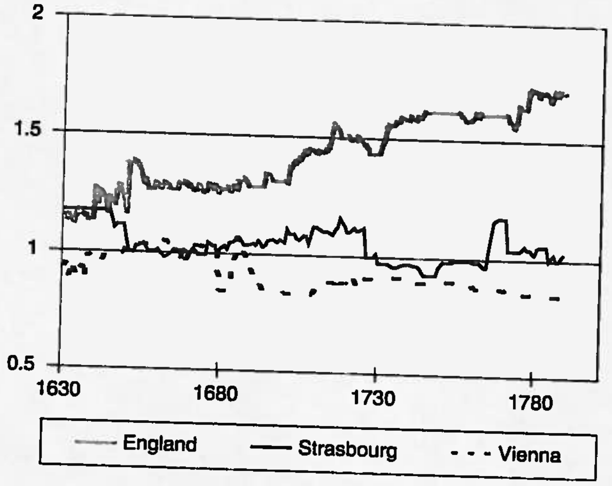

Figure 6.1 Wage relative to price of capital

The ratio of the wage relative to the price of capital was trendless in the early seventeenth century, and the differences between the cities were small. English labour was relatively cheap. The positions were reversed in the mid-seventeenth century when the series diverged, and English labour became increasingly expensive relative to capital. In contrast, the ratio of the wage to the price of capital declined gradually in Strasbourg and Vienna across the seventeenth and eighteenth centuries. The divergence in trends reflects the trajectories of nominal wages, which increased much more rapidly in Britain than elsewhere (e.g. Figure 2.1), rather than the cost of capital. This is a further blow to the institutionalists who maintain that Britain's superior institutions gave it cheaper capital. In the event, the incentive to mechanize production was much greater in England than in France, Germany or Austria.

The differences between Britain and other countries were even more pronounced in the case of energy. Figure 6.2 shows the ratio of the building wage rate to the price of energy in the early eighteenth century in important cities in Europe and Asia. For this calculation, the price of fuel was stated in terms of its energy content in millions of BTUs. The ratio is calculated for the cheapest fuel available in each city – coal in London and Newcastle, peat in Amsterdam, charcoal or firewood in the other cities.

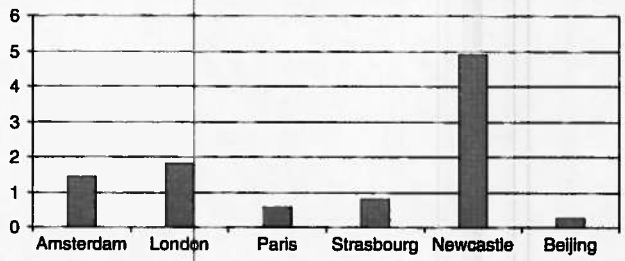

Figure 6.2 Price of labour relative to energy, early 1700s

Newcastle stands out as having the highest ratio of labour costs to energy costs in the world. To a degree, the high ratio reflects high British wages, but the low cost of coal was the decisive factor. Indeed, a similar ratio characterized the situation on all of the British coal fields and in the industrial cities (Sheffield, Birmingham and so forth) built on them. The only place outside of Britain with a similarly high ratio of labour to energy costs was probably the coal mining district around Liège and Mons in present-day Belgium. The high cost of labour relative to fuel created a particularly intense incentive to substitute fuel for labour in Britain. The situation was the reverse in China where fuel was dear compared to labour.

Why Britain's unique wages and prices mattered: substituting capital for labour

The British Industrial Revolution was the unfolding of a particular pattern of technical change. It was a path-dependent trajectory in which each step is explained (in part, at least) by the step that came before (David 1975, 1985, Dosi 1982, 1988, Arthur 1994). To understand why the technology of the British cotton industry or iron industry developed as it did, we must explain the first step in the trajectory. Those first steps were the famous macro-inventions of the eighteenth century.

The macro-inventions were made in Britain in the eighteenth century since Britain's high – and rising – wage induced a demand for technology that substituted capital and energy for labour. At the end of the middle ages, there was little variation across Europe in capital intensity. As the wage rose relative to the price of capital in Britain, it was increasingly desirable to substitute capital for labour and that is what happened. Sir John Hicks (1932, pp. 124–5) had the essential insight: 'The real reason for the predominance of labour-saving inventions is surely that . . . a change in the relative prices of the factors of production is itself a spur to innovation and to inventions of a particular kind – directed at economizing the use of a factor which has become relatively expensive.'[7]

We can clarify the influence of prices on invention, if we recognize that it involved the two stages that Edison called 'inspiration' and 'perspiration'. The important thing about the inspiration of the macro-inventions is that the idea they embodied came from outside the experience of the industry concerned. The idea of using coke as a blast furnace fuel was borrowed from industries like malting where it had been innovated as a fuel. Roller spinning was the adaptation of a technology (rollers) that was used in metallurgy and paper-making. The atmospheric steam engine was the application of knowledge discovered by seventeenth-century natural philosophers. Because the idea came from elsewhere, it could – and did – represent a radical change in practice, and that is why these ideas resulted in radical changes in factor proportions – the hallmark of macro-inventions. Hargreaves' spinning jenny is the exception that proves the rule. He thought it up by watching a spinning wheel. The invention of the spinning jenny looks like 'local learning' rather than an idea imported from elsewhere. While one expects local learning to result in minor changes, the spinning jenny, nevertheless, embodied a far-reaching change in factor proportions and, thus, qualifies as a macro-invention despite its origin.

The second stage of invention was research and development – the perspiration that turned a concept into a new product or a process. Leonardo da Vinci is famous as an 'inventor' since he sketched hundreds of novel machines, but his reputation is overblown in that he rarely did the hard work to turn drawings into functioning prototypes. Our interest is in the technologies that were *used* in the Industrial Revolution, and use required R&D as well as a eureka moment. While new ideas may not have been economically conditioned, R&D certainly was since the decision to incur costs to operationalize a technical idea was an economic one. As Machlup (1962, p. 166)

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[7] Economists have since debated how to formalize these ideas (David 1975, pp. 19–91, Temin 1971, Ruttan 2001, Ruttan and Thirtle 2001, Acemoglu 2003).

remarked, 'Hard work needs incentives, flashes of genius do not.' Prices influenced technological development through their effect on the profitability of R&D.

The essential idea is that inventors spent money to develop ideas when they believed the inventions would be useful, in particular, when their social benefits exceeded the costs of their invention. When this condition was satisfied, an inventor with an enforceable patent could recoup the development costs through royalties. Even when private gain was not the object – for instance, Abraham Darby II figured out how to make coke pig iron that was suitable for wrought iron but refused to patent the discovery – social utility was still the aim, so our analysis has force. Whether or not an inventor got a royalty, a mundane point is crucial: an invention was socially useful only if it was used. If it was not used, there was no point in inventing it. Invention, thus, depended on adoption. Adoption, in turn, depended on factor prices, and that meant that factor prices influenced R&D and hence invention.

Implicit in this analysis is the idea that firms undertaking R&D knew what they were aiming at, at least in economic terms. It would be hard to argue with this assumption in the case of the inventions that increased the use of coal, for they were clearly aimed at changing factor proportions in the direction of a cheaper input. The assumption is not as immediately obvious in the case of machines. Was Hargreaves aiming at saving labour with the spinning jenny and Arkwright with the water frame? MacLeod (1988, pp. 158–81) notes that patent applications rarely specified 'saving labour' as the goal, but also adds that such a declaration might have only caused trouble. In the case of machines, however, the assumption must be that the invention was aimed at saving labour. In 1757, the Reverend John Dyer described Wyatt and Paul's roller spinning machine with the lines:

> A circular machine, of new design
> In conic shape: It draws and spins a thread
> Without the tedious toil of needless hands.[8]

Twenty years later, Adam Smith (1776, p. 271) generalized the view that machines were *intended* to raise the capital–labour ratio and output per worker:

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[8] Quoted in the article, 'John Wyatt (Inventor)', www.wikipedia.org (2008).

> The intention of the fixed capital is to increase the productive power of labour, or to enable the same number of labourers to perform a much greater quantity of work . . . In manufactures the same number of hands, assisted with the best machinery, will work up a much greater quantity of goods than with more imperfect instruments of trade.

This idea was popularly accepted: anti-machine riots in the eighteenth century were based on the idea that machines cut jobs. Bentley (1780), who believed that the rioters were short-sighted (they failed to recognize that higher labour productivity would create more jobs in the long run by making Britain more competitive), nevertheless accepted their assumption that machines reduced employment per unit of output, for he called his book *Letters on the Utility and Policy of Employing Machines to Shorten Labour*. If this was the conventional assumption among the population at large, can we imagine that saving labour was far from the thoughts of the inventors of machines?

Eighteenth-century comments like these bear on a red herring in the analysis of factor prices and technical change: a high wage might not imply high labour costs if the high wage workers were more productive than the low wage workers. If true, the incentive to mechanize might then be reduced. In the modern world, workers in poor countries may be less productive than their better fed and better educated counterparts in rich countries, so the difference in wages overstates the difference in production costs. The same may have been true in the eighteenth century if high wage British labour was better nourished, for instance, than lower wage French labour. But clearly there are limits to this effect: the higher productivity of manufacturing workers in rich countries has not been enough to prevent firms from relocating factories to the developing world to take advantage of the low wage, nor has it stopped them from raising the capital–labour ratio in the developed world. Comparisons between rich and poor countries depend critically on the characteristics of particular workers and the requirements of the jobs at issue. And, by replacing human power with machines, mechanized factories reduced the importance of nutrition in job performance.

Eighteenth-century commentators suggest that nutritional or other differences between workers in England and her competitors were not enough to offset the higher wage earned by English workers. Bentley (1780, p. 4) said that the 'advancing price of manual labour' in British manufacturing was offset 'by adopting every ingenious improvement the human mind could invent' rather than by an improvement in the intrinsic productivity of British labour that rendered mechanization unnecessary. The French glass manufacturer Delaunay Deslandes was particularly convincing on this point, for he recognized that high British wages led to a better diet than their French counterparts could afford: the English ate meat and drank beer, while the French only had soup, vegetables and water. In reflecting on these facts, Deslandes did not wonder how the French could hope to compete against such well-nourished foreigners. Instead, he asked how the English ever hoped to compete against the French when British wages were so high. The answer was cheap coal that offset the high cost of English labour.[9] Either a cheaper input (e.g. coal) or a more mechanized technology was needed to offset the high British wage if the British ever hoped to compete internationally.

It is important to bring out another feature implicit in my analysis. Even though a macro-invention might have had revolutionary consequences, the first models were very inefficient from a commercial point of view. They scarcely turned a profit even under the most favourable circumstances, and they did not earn enough income to cover costs in most situations. For the same reason, their social savings (contribution to economic growth) was negligible in the beginning. Wyatt and Paul spent decades trying to make roller spinning pay, and never did succeed. Abraham Darby I could not produce pig iron that was suitable for refining into wrought iron, but he did succeed in developing a specialized niche market of thin-walled castings. The inefficiency of the early models of macro-inventions is the reason that their adoption was very sensitive to factor prices. R&D can be thought of as the process of designing a prototype that was efficient enough to cover its costs. Then it could be operated commercially and further knowledge gained through observation and modification (local learning). At that point, the phase of micro-improvements was reached. The great virtue of this phase was that it did not require specific finance since R&D was effectively funded through normal business operations. In time, the macro-invention might be so improved that it could be used everywhere and revolutionize the world. But that was not the state of play at the outset.

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[9] I quote Deslandes' comments in Chapter 4. See also Harris (1975).

Applying the model to Britain and China

Before seeing how macro-inventions were improved, we can look at two examples of how factor prices guided invention. The first relates to pottery kilns in England and China. In Britain, pottery was fired in round, up-draft kilns shown in Plate 6.1. These kilns were cheap to build but did not use energy efficiently. Much heat was lost as the draft left the kiln through the holes in the top. In Asia, on the other hand, kilns were designed to conserve energy. A common design was the 'down-draft climbing kiln' shown in Plate 6.2. These kilns were built on the slope of a hill. The kiln was a series of domes ('beehives') that were connected at the bottom. The walls were built thick to prevent heat loss. Each beehive had a firebox (but in the illustration only the first is shown). The hot air in the first chamber was not allowed to vent immediately into the second but was first forced down to ground level before leaving. As a result, much of its heat remained in the chamber, which reached an exceptionally high temperature. When the cooler (but still hot!) air entered the second chamber, the heat was passed on to the next batch of pottery. Another fire added more energy. The

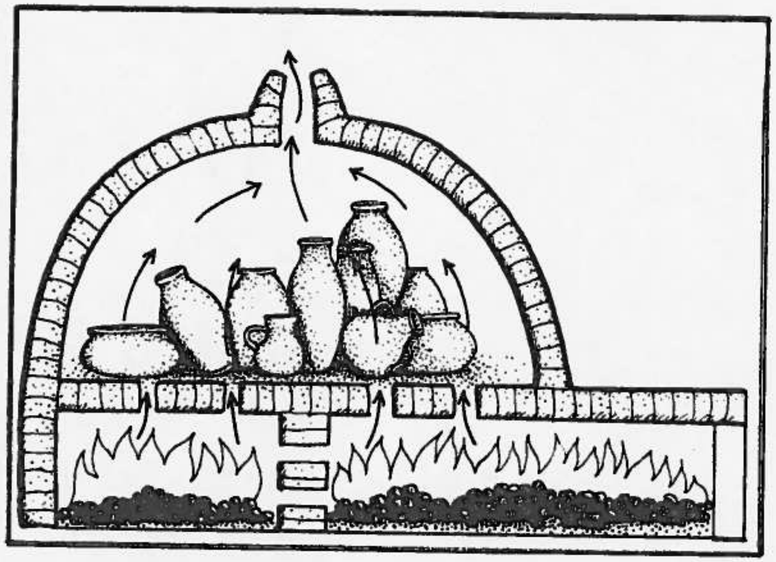

Plate 6.1 English kiln (image courtesy of Dianne Frank)

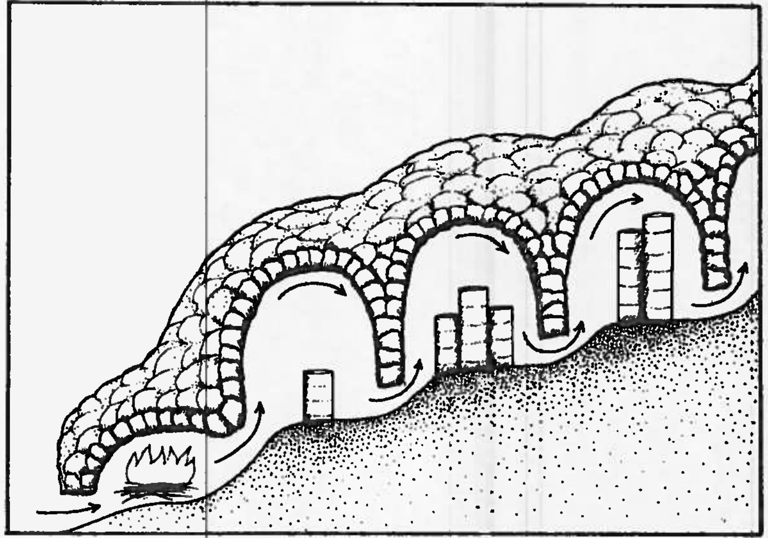

Plate 6.2 Chinese kiln (image courtesy of Dianne Frank)

process continued from chamber to chamber. In this way, very high temperatures were reached, and energy was conserved. Much capital was used, however, and many workers were employed stoking the various fires.

Neither the English nor the Chinese design was 'better' in an absolute sense. The best choice of design varied with the circumstances and depended on the prices of fuel, capital and labour. The Chinese developed a fuel-efficient design because energy was expensive, while the English saved capital and labour instead of energy because coal was so cheap.

Applying the model to Britain and France: the pin factory

We can see the same principles operating closer to home in the most famous production process of the eighteenth century – the pin factory described by Adam Smith in *The Wealth of Nations*. Smith argued that high productivity was achieved through a division of labour among hand workers. It is very likely that he derived his knowledge from Diderot and d'Alembert's *Encyclopédie* (1765, vol. V, pp. 804–7, vol. XXI, 'épinglier') since both texts divide the production process into eighteen stages, and that cannot be a coincidence.[10] Indeed, Smith seems to have used the *Encyclopédie* for the exact purpose that Mokyr (2002, pp. 68–72) suggests – to find out about the latest technology.

There is a difficulty, however. The *Encyclopédie*'s account is based on the production methods at L'Aigle in Normandy. This was not the state-of-the-art practice as carried on in Britain. The first high-tech pin factory in England was built by the Dockwra Copper Company in 1692, and it was followed by the Warmley works near Bristol in mid-century (Hamilton 1926, pp. 103, 255–7). The latter was a well-known tourist destination (Russell 1769), and Arthur Young visited it. Both mills were known for their high degree of mechanization, and they differed most strikingly from Normandy in the provision of power. In L'Aigle, machines were propelled by people turning flywheels that looked like spinning wheels. In contrast, the Warmley mill was driven by water power. Since the natural flow of the stream could not be relied on, a Newcomen steam engine was used to pump water from the outflow of the water wheel back into the reservoir that supplied it. 'All the machines and wheels are set in motions by water; for raising which, there is a prodigious fire engine, which raises, as it is said, 3000 hogsheads every minute' (Young 1771a, p. 138). Powering the mill in this way immediately eliminated the jobs of the wheel turners (their wages amounted to one-sixth of the cost of fabricating copper rod into pins) and probably other jobs as well. Many French workers, for instance, were employed scouring pins. This activity was done with large machines driven by water power at English needle factories at the time.[11] Arthur Young observed that the Warmley works 'are very well worth seeing'. It is a pity that Adam Smith relied on the French *Encyclopédie* to learn about the latest in technology rather than travelling with Arthur Young.

Why did the English operate with a more capital- and energy-intensive technology than the French? L'Aigle was on a river, and water power drove a forge in the town, so geography was not a bar (indeed, the steam engine at Warmley shows that water power was

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[10] Peaucelle (1999, 2005, 2007) has examined Smith's sources very carefully and identified several additional French publications that he argues Smith relied on. All of these sources describe production in Normandy.

[11] Early eighteenth-century water-driven scouring machinery is still in operation and can be seen at the Forge Mill Needle Museum, Redditch.

possible almost anywhere if you were willing to bear the cost of a steam engine). The Swedish engineer R. R. Angerstein (1753–5, p. 138) visited Warmley in the 1750s and noted that 'the works uses 5000 bushels of coal every week, which, because they have their own coal mines, only costs three Swedish "styfwer" per bushel', which was about half the Newcastle price.[12] In addition, English wages were considerably higher than French wages. Innovation in pin-making is an example of factor prices guiding the evolution of technology.

The second phase: a steam of micro-inventions

If innovation had stopped with the macro-inventions of the eighteenth century, the results would have been limited. While the Newcomen steam engine, for instance, was the technological marvel of 1712, it could do little more than pump water and was grossly inefficient by later standards. It took almost a century before a steam engine could directly drive machinery and a century and a half before steam was cheaper than sail on the tea route from China to Britain. This progress was the result of a vast stream of micro-inventions.

Micro-inventions differed from macro-inventions in three respects. First, micro-inventions were not generally biased technical changes that increased the demand for inputs that were abundant and cheap in Britain. Instead, micro-inventions were likely to be neutral technical improvements. In some cases, they even reversed the bias of the macro-inventions and saved inputs that were abundant in Britain. Thus, Newcomen's steam engine increased the demand for coal, but subsequent improvements like Watt's separate condenser were aimed at reducing energy consumption.

The gradual improvement of the macro-inventions had implications that we observe in the eighteenth and nineteenth centuries. At first, as the micro-inventions were made, Britain increased her technological lead over other countries. Moreover, countries with lower wages and more expensive energy still did not adopt the new British technology even though it was more modern, indeed, increasingly so. Thus, the coke blast furnace of the 1780s was more efficient that the furnace of the 1730s, but the French still did not use it. This reluctance has given rise to debates about the quality of French entrepreneurs and

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[12] I thank Martin Dribe for help in deciphering the Swedish styfwer.

engineers, but the reality was that the blast furnace of the 1780s still used too much coal to be profitable in France where coal was very dear. In the next seventy years, British engineers reduced the use of all inputs – coal, ore, labour and capital – so much that coke smelting became more profitable than charcoal smelting in France. At that point, the French shifted to mineral fuel smelting very quickly: a 'tipping point' was reached. The French jumped directly to the most advanced blast furnace technology and skipped all of the intermediate stages through which the British progressed. Britain's competitive advantage had been based on the invention of technology that benefited it differentially. It is ironic that the success of Britain's engineers in perfecting that technology destroyed the country's competitive advantage.

A second difference between macro- and micro-inventions was in the inspiration for the inventions. While the ideas behind most macro-inventions came from outside the immediate industrial experience, the ideas for micro-inventions often originated in the study of that experience. Such ideas are called local learning. When Watt, for instance, invented the separate condenser, he began with a model of the Newcomen engine to see how it could be improved. He was also involved in erecting several engines, so he saw how they worked in practice and could try out his improvement. Learning in this way meant that the inventor was as likely to find an improvement that saved capital as one that saved labour. Since any change that cut costs was an improvement, there was no selection mechanism that generated a bias to save one input rather than another.[13] Of course, the possibilities of invention were affected by the characteristics of the materials themselves – no one has yet contrived to make a pound of cotton yarn with less than a pound of raw cotton – and by extraneous scientific discoveries and economic developments that created new factor price configurations, but reliance on local learning imparted a tendency towards neutrality in the second, micro-improvement phase of technological progress.

The third difference between macro- and micro-inventions lay in business behaviour. Because macro-inventions involved radical departures from existing practice, the R&D they entailed was expensive. Unless one was rich and prepared to spend his fortune like Edmund

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[13] The essays collected in David (1975, pp. 1–191) are the most penetrating analysis of learning and technical change in economic history. My analysis draws on them.

Cartwright, the inventor of the power loom, external sources of finance had to be found. Venture capitalists, known as 'projectors' in the eighteenth century, usually became partners and received a share of the profits of the business. The invention was patented to secure those profits. Thus, the macro-inventions of the eighteenth century gave rise to the modern trilogy of R&D, venture capital and patent protection (Dutton 1984, MacLeod 1988, Sullivan 1990).

Micro-inventing was often a more collective enterprise (Rosenberg 1976, 1982). Since learning was local, it was often cheaper than macro-inventing, so the needs for external finance and patent protection were reduced. By sharing information, inventors could learn from each other and become more efficient. An important case in point was the perfection of the Cornish pumping engine in the nineteenth century which pointed the way to fuel economy in steam engines generally. These improvements were effected by the exchange of technical and economic information among all of the mines in Cornwall (Nuvolari 2004a, 2004b). Even when inventors patented their improvements, there was often also an exchange of knowledge and a cooperative approach to technical progress. Engineering societies played an important role in this regard. As collective learning became institutionalized, the tendency for technology to improve neutrally was increased.

The biographies of three macro-inventions

In the next three chapters, I will use the framework of this chapter to tell the stories of three of the great inventions of the Industrial Revolution: the steam engine, mechanical spinning, and smelting iron with coke.

First, I tell the story of the macro-invention. I begin with conception: what was the inspiration for the invention? Was it local learning, scientific discovery, or copying? How much genius was involved? Then I analyze birth: how much perspiration was required? How was R&D organized and financed? Then I consider the pay-off to this exertion in terms of the growth in productivity. How did the invention affect input requirements? Was it a biased technical change? Was it profitable to use the technique in Britain but not abroad? Does invention look sensible in terms of the economics of R&D?

Secondly, I analyze the long history of improvements to the macro-invention. What were the significant engineering improvements? Were they due to local learning? Did they lead to neutral technical progress in which all inputs were saved? Indeed, they were and did. And, by the middle of the nineteenth century, the macro-inventions of the Industrial Revolution lost their British bias and became globally useful technologies.

Appendix

Invention and the evolution of technology can be illustrated with a standard isoquant model.[14]

Phase I: macro-inventions

Macro-inventions are characterized by a radical change in factor proportions. This bias of the technical change interacted with factor prices and affected the incentives to undertake research and development. There are five important points to make:

1. A biased technical change saved one input disproportionally and reduced costs the most where that input was most expensive.
2. Techniques were worth inventing only if they were used.
3. A new technique was not worth using everywhere.
4. Countries with high wages found it profitable to develop a broader range of techniques with high capital–labour ratios than did low wage countries.
5. Larger markets increased the profitability of R&D and led to more invention.

These points are illustrated in Figure 6.3, which contrasts high wage and low wage countries. The curved isoquant through H and L connects the quantities of capital and labour needed to produce one unit of output. H is the input combination used by the high wage country, and it has a higher capital–labour ratio than the input combination L used by the low wage country. The straight lines tangent to the isoquant at H and L connect equal cost combinations of capital (K) and labour (N) where the unit cost of production is $C = rK + wN$ and where r and w are the rental price of capital and the wage rate. Each straight line

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[14] Harley (1971) and David (1975, p. 89) use similar diagrams and Harley (1973) emphasizes 'the persistence of old techniques'.

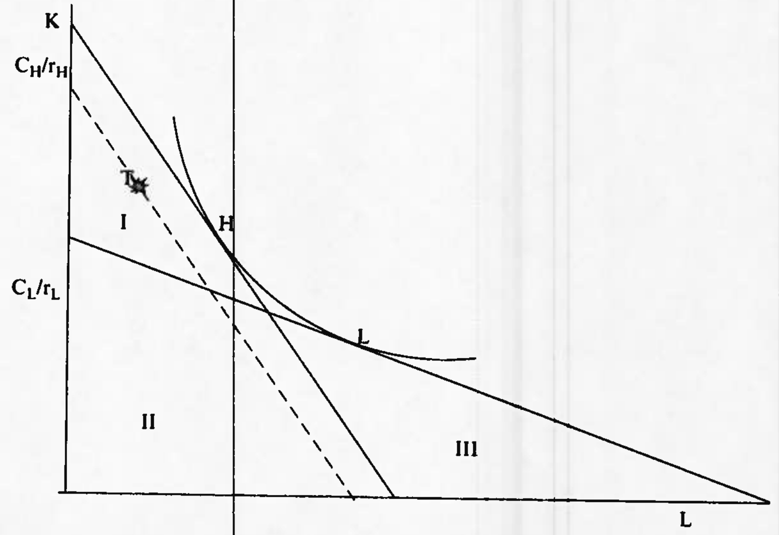

Figure 6.3 Phase 1: macro-inventions

plotted in Figure 6.3 is of the form K = C/r + (w/r)N. Its slope equals the wage relative to the price of capital (hence a steeper line denotes the high wage country) and C/r is the point where the line intersects the K axis. Hence, a higher intersection point indicates higher production cost (C). In Figure 6.3, C_H/r_H indicates the unit cost in the high wage country, and C_L/r_L the cost in the low wage country.

Now consider a potential new technology represented by the point T connecting a new combination of capital and labour that can produce one unit of output. T is a biased technical change: It uses more capital and less labour than either H or L. Would T be used? It would if and only if it lowered costs, and that is the case for the high wage country. We know this since a straight line through T that is parallel to the isocost line through H (hence, represents the same w/r) has a lower intersection point on the K axis and, hence, represents lower unit costs. For the low wage country, T would raise costs by the same argument. A technology like T is worth using – and hence worth inventing – only for the high wage country.

The two isocost lines divide the area below them into three spaces. New technologies in I would be adopted only by the high wage country, technologies in III only by the low wage country, and technologies like II by either country. Some new technologies are useful to any country, while others are useful only to countries in particular factor price situations. Factor prices affect technological evolution because the adoption and invention of new techniques in sectors I and III depends on factor prices.

The high wage and the low wage countries had opposite incentives to invent technique T. It would be pointless for the low wage country to invent it since it would not be used. It might be worth inventing in the high wage country, but the incentive depends on benefits net of development costs. A technique like T in sector I would lower operating costs for high wage countries, and that saving generates the demand for the technology, i.e. creates a return for someone to invent it. But invention requires research and development to actualize the idea. Whether the demand for the technology is enough to motivate its development depends on the balance between the saving in operating costs and the cost of the R&D. Scale plays a role here since the R&D cost must be amortized over the output and compared to the reduction in unit operating costs. The total cost of production (inclusive of R&D) with the new technique is C* = C + D/q where D is the development cost and q is total production. The total cost line inclusive of R&D costs is K = C* + (w/r)N = C/r + (D/q)/r + (w/r)N, i.e. the K intercept shifts up by the amortized R&D cost, so the total cost line is above the old one. The larger is q, the less is the upward shift in the isocost line inclusive of R&D cost. Two possibilities need to be distinguished at this stage. The first is that the isocost line rises but remains below the isocost line with the old technique. In that case, it is profitable to develop (i.e. invent) the new technique T. The second possibility is that the new isocost line rises above the original isocost line. In that case, it is not profitable to invent the new technique because the market is too small. Of course, if some other country or countries paid the R&D costs and the new technology were freely available, it would be adopted because it cuts operating costs. The size of the market affected the profitability of invention through the amortization of R&D costs.

Figure 6.3 identifies the conditions under which R&D was profitable, and they drove much private sector R&D. They also highlight the shortcomings of non-commercial R&D like some well-known technology initiatives of the French state. One was Cugnot's fardier, a steam tractor developed by the military to pull cannon across fields. Cugnot built a high-pressure steam engine and installed it on a vehicle. The fardier was a technical success, but the project was abandoned since it consumed too much fuel and sank into the mud. High-pressure steam engines were successfully used for traction only when both problems were solved by putting them on rails to pull wagons in British coal mines. A second example was Vaucanson's fully automated silk loom. This was a tremendous technological achievement, but it was never used commercially since it was far too capital intensive (Doyon 1966). These technologies show the force of Figure 6.3 in that they were not profitable to invent because they were not profitable to use.

Phase II: micro-inventions

Figure 6.4 shows the path of development if the British macro-invention unleashed a stream of micro-improvements that were neutral.[15] Neutrality means that all inputs would be saved in equal proportion, and technology would evolve along the straight line from T towards the origin.

The trajectory of micro-improvements in Figure 6.4 has important features that resonate with the industrial history of the last two hundred years. These include:

- Initially, the high wage country, which is the world's technological leader, builds up its lead. Invention and R&D are occurring there, and productivity is rising.
- In contrast, nothing much happens in the low wage country. They do not adopt the modern technology of the high wage country. Questions inevitably arise about the quality of their entrepreneurs and engineers.
- There is a 'tipping point', however, once the technology is improved to the point X where the path of technical improvement crosses the price line of the low wage country. At that point, it becomes suddenly profitable to adopt British technology. (A dotted isocost line for the low cost country is drawn through an input combination on the line from T to the origin and below X. The dotted isocost line is below the original isocost line for the low wage country and, therefore, represents cheaper production.)
- The low wage country finds that it pays to leap over many stages of technological development and go directly from L to the latest British technology. Catch-up is very rapid – a great spurt (Gerschenkron 1962). The Industrial Revolution spreads around the globe.

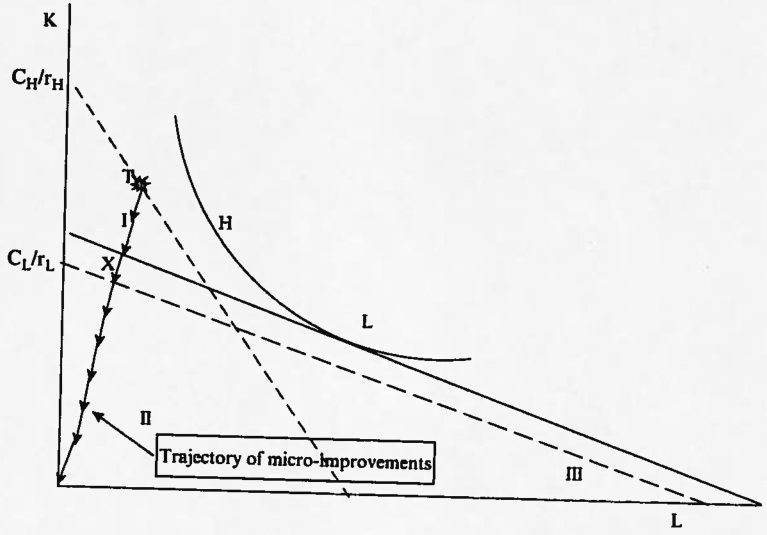

Figure 6.4 Phase 2: the trajectory of micro-improvements

- Britain's competitive advantage had been based on the invention of technology that benefited it differentially. It is ironic that the success of Britain's engineers in perfecting that technology destroyed the country's competitive advantage.

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[15] Harley (1971) and David (1975, pp. 66, 71, 75) use similar diagrams.