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Why the industrial revolution was British: commerce, induced invention, and the scientific revolution[1]

By R. C. ALLEN

Britain had a unique wage and price structure in the eighteenth century, and that structure is a key to explaining the inventions of the industrial revolution. British wages were very high by international standards, and energy was very cheap. This configuration led British firms to invent technologies that substituted capital and energy for labour. High wages also increased the supply of technology by enabling British people to acquire education and training. Britain's wage and price structure was the result of the country's success in international trade, and that owed much to mercantilism and imperialism. When technology was first invented, it was only profitable to use it in Britain, but eventually it was improved enough that it became cost-effective abroad. When the 'tipping point' occurred, foreign countries adopted the technology in its most advanced form.

The industrial revolution is one of the most celebrated watersheds in human history. It is no longer regarded as the abrupt discontinuity that its name suggests, for it was the result of an economic expansion that started in the sixteenth century. Nevertheless, the eighteenth century does represent a decisive break in the history of technology and the economy. The famous inventions—the spinning jenny, the steam engine, coke smelting, and so forth—deserve their renown, for they mark the start of a process that has carried the west, at least, to the mass prosperity of the twenty-first century.[2] The purpose of this article is to explain why they were invented in Britain, in the eighteenth century.

Explaining the industrial revolution is a long-standing problem in social science, and all manner of prior events have been adduced as causes.[3] Recent research has emphasized non-economic factors like the British constitution[4] or British culture,[5]

[1] This article is the text of the Tawney Lecture, delivered on 5 April 2009 at the Economic History Society Annual Conference, University of Warwick.

[2] There has been a debate about the breadth of technological progress during the industrial revolution with Crafts, *British economic growth*; Harley, 'Reassessing'; Crafts and Harley, 'Output growth'; and Crafts and Harley, 'Simulating', arguing that productivity growth was confined to the famous, revolutionized industries in the period 1801–31, while Temin, 'Two views', has argued that many more industries experienced productivity growth. Whatever one believes about 1801–31, it is clear that many non-revolutionized industries experienced productivity growth between 1500 and 1850. The incentives to invent discussed in this article applied to all industries, not just the famous ones I discuss here.

[3] Hartwell, *Causes*, and Mokyr, 'Editor's introduction', provide surveys. Crafts, 'Industrial revolution in England', has suggested that Britain's lead was fortuitous.

[4] Proponents of this view include North and Weingast, 'Constitutions'; De Long and Schleifer, 'Princes and merchants'; LaPorta, Lopez-de-Silanes, Schleifer, and Vishny, 'Law and finance'; Acemoglu, Johnson, and Robinson, 'Rise of Europe'. For critical or contrary perspectives, see Clark, 'Political foundations'; Epstein, *Freedom and growth*; Quinn, 'Glorious revolution's effect'; Hoffman, Postel-Vinay, and Rosenthal, *Priceless markets*; Pomeranz, *Great divergence*; Mathias and O'Brien, 'Taxation'; Mathias and O'Brien, 'Incidence'; Hoffman and Norberg, *Fiscal crises*; and Bonney, *Rise*.

[5] Landes, *Unbound Prometheus*; Clark and Jacks, 'Coal'.

both of which have been alleged to be superior. The matter, however, is controversial: while certain legal arrangements and cultural predispositions may have favoured economic development, it is not at all clear that Britain was alone in possessing them. In this article, I sidestep these debates by taking a different approach and emphasizing the importance of economic incentives as a cause of the industrial revolution. The essence of the industrial revolution was new technology, and I trace the links from Britain's success in the world economy in the early modern period to the technological breakthroughs of the eighteenth century.

I focus on the sources of invention and analyse these in terms of the demand and supply of new technology. The empirical base of this analysis is international comparisons of wages and prices. These comparisons show that eighteenth-century Britain had a unique wage and price structure. British wages were exceptionally high compared with wages in other parts of Europe and in Asia, while the prices of capital and energy were exceptionally low. The price and wage structure 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. The *supply* of technology was also augmented by the high real wage. It 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 and Stewart, and Mokyr have emphasized the importance of Newtonian science, the Enlightenment, and 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.[6] 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 from some points of view: France was in the lead in many industries with new techniques to its credit in paper, clocks, glass, and textiles, for instance. 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 it did and why they were so transformative.

This article takes as its point of departure Edison's famous observation that 'invention was 1% inspiration and 99% perspiration'. That suggests that inventing the industrial revolution was mainly a story about research and development (R&D) (perspiration). R&D is an economic activity with distinctive features. As Machlup remarked, 'Hard work needs incentives, flashes of genius do not'.[7] By

[6] Jacob, *Scientific culture*; Jacob and Stewart, *Practical matter*; Mokyr, 'Editor's introduction'; idem, *Gifts of Athena*.

[7] Machlup, *Production*, p. 166.

concentrating on the R&D and the incentives to undertake it, we can get a much deeper understanding of why the industrial revolution happened when and where it did.

Britain's unique wage and price structure was the pivot around which the industrial revolution swung. Logically, the next question, therefore, is to explain what determined the wages and prices. They turn out to have been the result of Britain's great success in the international economy in the early modern period, and that relationship will also be examined. The answer to the grand question of how the industrial revolution was related to the early modern economy is this: the commercial and imperial expansion of Britain created a unique structure of wages and prices, and that price structure, in turn, prompted the technological breakthroughs of the eighteenth century by increasing the demand for inventions that substituted capital and energy for labour, and by generating a population that was exceptionally able to respond to those incentives due to its high rates of literacy, numeracy, and craft skills. The spread of scientific culture may have had a reinforcing effect. Some important scientific developments contributed to this advance, but they would not have been acted upon without a demand for the technologies that applied them.[8]

I

Since invention was an economic activity, its pace and character depended on factors that affected business profits including, in particular, input prices. It is easier to understand why the industrial revolution happened in eighteenth-century Britain if we compare wage rates and energy prices in the leading economies of the day. In these comparisons, Britain stands out as a high-wage, cheap-energy economy.

Our views of British wages are dominated by the standard of living debate. Even optimists who believe the real wage rose in the industrial revolution accept that wages were low in the eighteenth century. They were certainly lower than they are today, but recent research in wage and price history shows that Britain was a high-wage economy in four senses. Firstly, at the exchange rate, British wages were higher than those of its competitors. Secondly, high silver wages translated into higher living standards than elsewhere. Thirdly, British wages were high relative to capital prices. Fourthly, wages in northern and western Britain were exceptionally high relative to energy prices.

These trends are illustrated in figures 1–4. These figures were constructed from databases of wages and prices assembled from price histories written since the middle of the nineteenth century.[9] The typical price history is based on the archives of an institution that lasted for hundreds of years—colleges and hospitals are favourites. Historians work through their accounts, recording the quantity and price of everything bought or sold, and draw up tables of the annual averages. Usually prices are found for a range of agricultural and food stuffs as well as cloth,

[8] The argument is developed more fully in Allen, *British industrial revolution*.

[9] The data are referenced and described in greater detail in Allen, 'Great divergence in European wages'; idem, 'Poverty and progress'; idem, 'Timber crisis'; idem, 'India in the great divergence'; idem, *British industrial revolution*; idem, 'Industrial revolution in miniature '; Allen, Bassino, Ma, Moll-Murata, and van Zanden, 'Wages, prices, and living standards'.

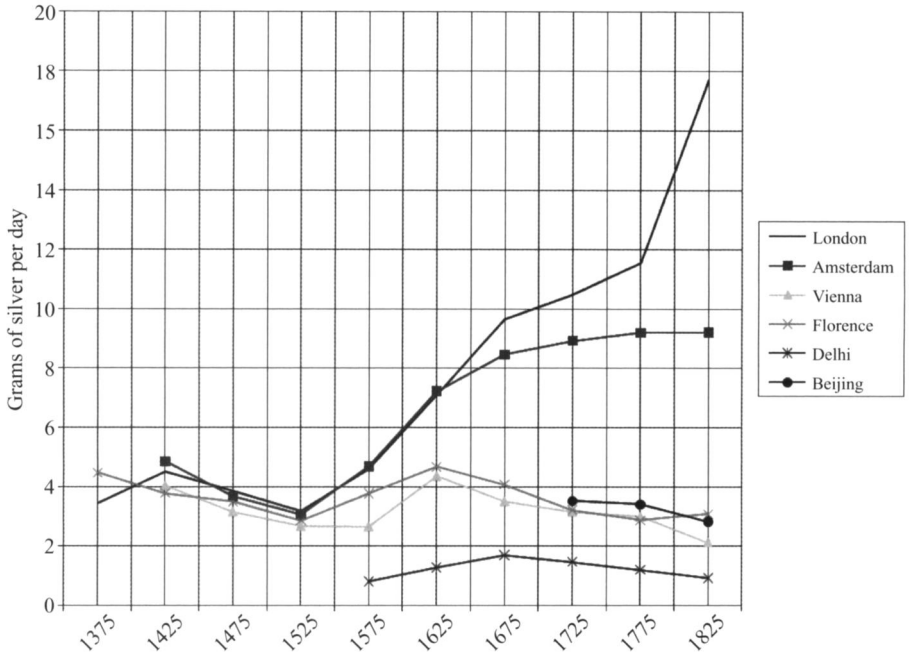

Figure 1. *Labourers' wages around the world*
Source: See text.

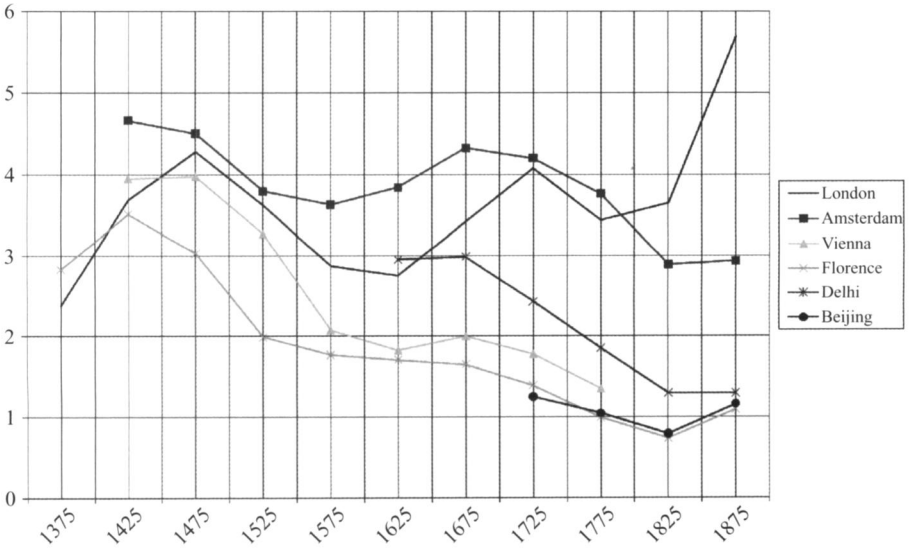

Figure 2. *Subsistence ratio for labourers: income relative to cost of subsistence basket*
Source: See text.

Figure 3. *Wage rate relative to price of capital*
Source: See text.

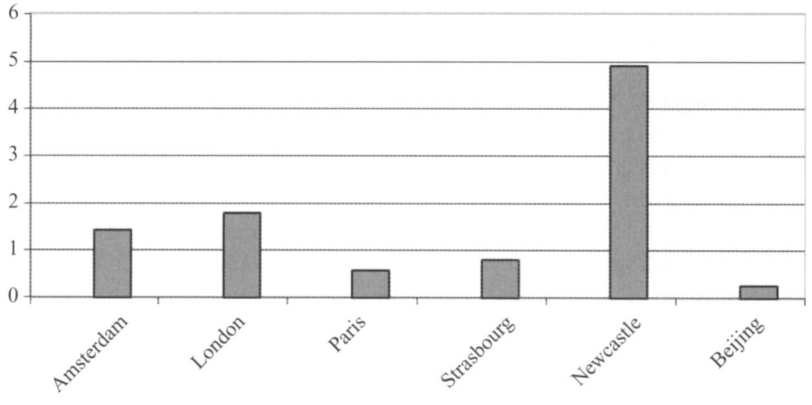

Figure 4. *Wage rate relative to price of energy*
Source: See text.

fuel, candles, building materials, implements, and a miscellany of other items. Wages and salaries are often also recorded. The commodities are measured in local weights and measures, and prices are stated in local units of account, and these must be converted to international standards. Prices histories have been written for many European cities, and the research is being extended to Asia. By putting all of this material in the computer, international comparisons are becoming possible for the first time, and they are redefining our understanding of economic history. In particular, they throw new light on the origins of the industrial revolution, as we shall show.

Figure 1 shows the history of nominal wages of building labourers in leading European and Asian cities from the middle ages to the industrial revolution. The various units of account in which the data were recorded have been converted to grams of silver, since silver coins were the principal medium of exchange. The figure shows that the divergence in nominal wages was minimal in Europe at the

end of the late middle ages. There was little wage inflation subsequently in eastern Europe. Wages in western Europe rose during the price revolution (1550–1620). Thereafter, there was a three-way split, with silver wages falling in southern Europe, levelling out in the Low Countries, and continuing to rise in London. From the late seventeenth century onwards, London wages were the highest recorded.

London wages rose above those elsewhere in Britain in the sixteenth century. By the late seventeenth century, however, wages in southern English towns like Oxford were rising to close the gap. Wage movements in northern England were more erratic. In the late seventeenth century, builders' wages in cities like York were as high as those in Oxford. Wage growth ceased in the north in the early eighteenth century, however, so the region fell behind the south in nominal wages, although the level was still higher than in most parts of the European Continent. Fast wage growth towards the end of the eighteenth century brought the north to the same level as the south, however, and all parts of England had exceptionally high silver wages.[10]

Comparisons with Asia further emphasize the high wages in eighteenth-century Britain. In Beijing, Canton, Japan, and Bengal, labourers earned between one and two grams of silver per day—less than half the wage in central or eastern Europe and a smaller fraction of earnings in the advanced economies of the north-west of the Continent.[11]

Did Britain's high nominal wages translate into high living standards or were they offset by high prices in Britain? To explore this issue, welfare ratios have been computed for leading cities. Welfare ratios are defined as full-time annual earnings[12] divided by the cost of a basket of consumer goods sufficient to keep a family at a specified standard of comfort—in this case at minimal subsistence. Baskets are constructed with most spending on the grain that was cheapest in each locality (for example, oats in northern Europe, polenta in Florence, sorghum in Beijing, and millet in Delhi). Very small portions of meat, peas or beans, butter or oil, cloth, and fuel, and a small allowance for housing are also included. Consumption is set at the low level of 1,940 kilocalories per day for an adult male, with other family members proportioned accordingly. Calculations with baskets corresponding to a more affluent lifestyle have also been undertaken, and the relative rankings are unchanged.

Figure 2 plots the welfare ratios for the cities in figure 1. The population decline caused by the Black Death meant that real incomes were high everywhere in the fifteenth century. Welfare ratios in London and the Low Countries were trendless across the early modern period, although there were oscillations in the series. Moreover, fully employed workers in these regions earned three to five times the cost of the subsistence lifestyle. They spent their extra income on a superior diet (with bread, beer, and much more meat) and more non-food consumer goods including some of the luxuries of the 'consumer revolution' of the eighteenth

[10] Gilboy, *Wages*; Allen, *Great divergence*; idem, 'Poverty and progress'.

[11] Özmucur and Pamuk, 'Real wages'; Allen, 'India in the great divergence'; Allen et al., 'Wages, prices, and living standards'; cf. Allen, Bengtsson, and Dribe, *Living standards.*

[12] European building workers were paid by the day, and I assume that 250 days was a full year's work, making allowance for Sundays, religious holidays, and erratic employment. Many Asian wages are based on monthly earnings, and I assume employment for 12 months.

century.[13] In contrast, real living standards fell dramatically across the Continent, reaching a level of about one. In eighteenth-century Florence and Vienna, fully employed building workers earned only enough to maintain their families at rock bottom subsistence. There was no surplus for bread, meat, beer, or wine, let alone imported luxuries. Real wages also fell sharply in provincial England in the sixteenth century, but even at the trough labourers in Oxford earned at least 50 per cent more than bare bones subsistence. The nominal wage inflation of the late seventeenth century meant that welfare ratios in Oxford were between 2.5 and 3.0 in the eighteenth century.

If we extend the comparisons of living standards to Asia, English performance looks even more impressive. Low silver wages in the East were not counterbalanced by even lower food prices. Welfare ratios for labourers in Canton, Beijing, and Japan were about one in the eighteenth and nineteenth centuries—as low as those in the backward parts of Europe. Mass demand for manufactures was very limited across Asia, since most consumer spending was directed towards basic necessities.

The earnings of craftsmen (carpenters, masons, and so forth) followed the same trends as labourers in all countries. Skilled workers, however, earned more than the unskilled, so their welfare ratios were higher everywhere. Craftsmen in London or Amsterdam earned six times what was required to purchase the subsistence basket, while their counterparts in Germany or Italy only 50 per cent more than that standard. Craftsmen in north-western Europe spent much of their surplus income on more food and better-quality food. Nonetheless, the mass market for consumer goods was much larger in Britain and the Low Countries than in most of Europe.

A third sense in which Britain was a high-wage economy was in terms of the wage rate relative to the price of capital. Figure 3 plots the ratio of a building labourer's daily wage relative to an index of the rental price of capital in northern England, Strasbourg, and Vienna. The rental price of capital is an average of price indices for iron, nonferrous metals, wood, and brick, multiplied by an interest rate plus a depreciation rate. Strasbourg and Vienna were chosen since long series of wages and prices are available for those cities, and their data look comparable to those of most of Europe apart from the Low Countries. The series reflect differences in the price of capital across space as well as over time.

The ratio of the wage relative to the price of capital was similar in all of the cities in the first half of the seventeenth century. Then the series diverged. In England, labour became increasingly expensive relative to capital from 1650 onwards. This rise reflects the inflation of nominal British wages at the time. 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 incentive to mechanize production was much greater in England than in France, Germany, or Austria.

Finally, there is a fourth sense in which labour was costly in industrializing Britain. That involves a comparison of wages to the price of fuel. Figure 4 is a bar graph of the ratio of the building wage rate to the price of energy in the early

[13] Shammas, *Pre-industrial consumer*; McKendrick, Brewer, and Plumb, *Birth*; de Vries, 'Purchasing power'; Fairchilds, 'Production'; Weatherill, *Consumer behaviour*; Berg and Clifford, *Consumers and luxury*; Berg, *Luxury and pleasure*.

eighteenth century in important cities in Europe and Asia. In this ratio, the price of a kilogram of fuel was divided by its energy content, so energy prices are expressed as grams of silver per million BTUs (British Thermal Units). 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.

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 coalfields 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. The Chinese invented very large kilns for firing their pottery because such kilns had a high ratio of volume to surface area and so conserved heat. The reverse was true in Britain where kilns were small and thermally inefficient.

II

Britain's unusual wages and prices were due to two factors. The first was Britain's success in the global economy, which was in part the result of state policy. The second was geographical—Britain had vast and readily worked coal deposits.

In pre-industrial Europe, real wages moved inversely to the population. As figure 2 indicates, the real wage rose in Britain and Italy after the Black Death of 1348/9, which cut the population by about one-third. As population growth resumed, the real wage fell in most of Europe between the fifteenth century and the eighteenth. The Low Countries were an important exception to this trend. Real wages fell in rural England in the sixteenth century, but London bucked the trend in the same way as Antwerp and Amsterdam, and indeed, as we have seen, living standards rose generally in southern England from 1650 onwards. Why were England and the Low Countries successful?

The superior real wage performance of north-western Europe was due to a boom in international trade. The English boom began with the export of 'new draperies' in the late sixteenth century. These were light woollen cloths made in East Anglia and exported to the Mediterranean through London. Between 1500 and 1600, the population of London grew from about 50,000 to 200,000 in response to the trade-induced growth in labour demand. During the Commonwealth, Cromwell initiated an active imperial policy, and it was continued through the eighteenth century.[14] In a mercantilist age, imperialism was necessary to expand trade, and greater trade led to urbanization. Between 1600 and 1700, London's population doubled again, and by 1800 it approached one million. In the eighteenth century, urbanization picked up throughout England as colonial trade increased and manufacturing oriented to colonial markets expanded. Between 1500 and 1800, the fraction of the English population living in settlements of more than 5,000 people increased from 7 per cent to 29 per cent. The

[14] P. K. O'Brien, 'It's not the economy, silly, it's the navy' (unpub. paper, 2006).

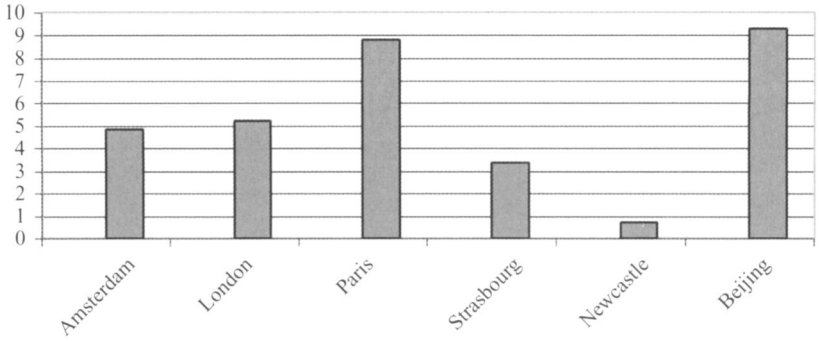

Figure 5. *Price of energy, early 1700s*
Source: See text.

share of the workforce in agriculture dropped from about 75 per cent to 35 per cent. Only the Low Countries, whose economies were also oriented to international trade, experienced similarly sweeping structural transformations. In the eighteenth century, the Dutch and the English had much more trade per capita than other countries in Europe. Econometric analysis shows that the greater volume of trade explains why their wages were maintained (or increased) even as their populations grew.[15]

Coal deposits were a second factor contributing to England's unusual wage and price structure. Coal has a long pedigree as an explanation for Britain's industrial success, and Wrigley put it on the modern research agenda.[16] I add two points to the discussion.

First, coal was not just abundant in Britain—it was cheap, at least in northern and western Britain on or near the coalfields. Figure 5 shows the price of energy in leading cities in the early eighteenth century. London did not have particularly cheap fuel at that time; Newcastle, however, did. The difference in the energy price between the two cities equals the cost of shipping the coal from the Tyne to the Thames. Despite an ocean route, transportation accounted for most of the price of coal in London. Coal prices at other cities in northern and western Britain were similar to those in Newcastle—at least once canal improvements reduced internal shipping costs. Except perhaps southern Belgium, no region anywhere in the world had the same combination of large population and cheap energy. Belgian coal output, however, was only 13 per cent of Britain's in 1800, and the return from inventing coal using technology was correspondingly reduced.

Cheap fuel was important for two reasons. Firstly, inexpensive coal raised the ratio of the price of labour to the price of energy (figure 4), and thereby contributed to the demand for energy-using technology. In addition, energy was an important input in the production of metals and bricks, which dominated the index of the price of capital services. Cheap energy contributed to the fall in capital prices relative to wages, and thus contributed to the incentive to substitute capital for labour.

[15] Allen, 'Poverty and progress'.
[16] Jevons, *Coal question*; Nef, *Rise*; Hatcher, *History*; Smil, *Energy*; Pomeranz, *Great divergence*; Sieferle, *Subterranean forest*; Wrigley, *Continuity*.

Secondly, coal was a 'natural' resource, but the coal industry was not a natural phenomenon. Some coal was mined in the middle ages.[17] It was the growth of London in the late sixteenth century, however, that caused the coal industry to take off. As London grew, the demand for fuel expanded, and the cost of firewood and charcoal increased sharply as fuel was brought from greater distances. Coal, on the other hand, was available in unlimited supply at constant real cost from the fifteenth to the nineteenth century.[18] In the late middle ages, coal and charcoal sold at about the same price per BTU in London. The market for coal was limited to blacksmithing and lime burning. In all other uses, sulphur made coal an inferior fuel. As London's population exploded in the late sixteenth century, the demand for fuel rose, as did the prices of charcoal and firewood. By 1585, wood fuel was selling for twice the price of coal per BTU. That differential made it worthwhile for buyers to figure out how to substitute coal for wood—in fact, a difficult problem[19]—and shipments of coal from Newcastle to London began their rapid growth. The take-off of the coal industry was thus due to the growth of London. Since this was due to the growth of international trade, the exploitation of Britain's coal resources was the result of the country's success in the global economy as well as the presence of coal in the ground.

The Dutch cities provide a contrast that reinforces the point and throws light on the important question of why the industrial revolution happened in Britain rather than the Netherlands.[20] In an important respect that question is badly formed. The cities of the Low Countries were the analogues of London, but the industrial revolution happened on the coalfields of northern and western Britain where energy was much cheaper. Their counterparts were the coal deposits that stretched from north-eastern France across Belgium and into Germany. This coal was as useful and accessible as Britain's. With the exception of the mines near Mons and Liège, however, Continental coal was largely ignored before the nineteenth century. The pivotal question is why city growth in the Netherlands did not precipitate the exploitation of Ruhr coal in a process parallel to the exploitation of northern English coal. Urbanization in the Low Countries also led to a rise in the demand for fuel. In the first instance, however, it was met by exploiting Dutch peat. This checked the rise in fuel prices, so that there was no economic return to improving transport on the Ruhr or resolving the political-taxation issues related to shipping coal down the Rhine. Once the Newcastle industry was established, coal could be delivered as cheaply to the Low Countries as it could be to London, and that trade put a ceiling on the price of energy in the Dutch Republic that forestalled the development of German coal. This was portentous: had German coal been developed in the sixteenth century rather than the nineteenth, the industrial revolution might have been a Dutch-German breakthrough rather than a British achievement.

While the high-wage economy of London led to the exploitation of cheap coal, the availability of cheap energy also sustained the high-wage economy. British businesses could pay high wages and compete in the international economy only

[17] Hatcher, *History*.

[18] The real price of coal was constant from 1450 to 1850. See also Clark and Jacks, 'Coal'

[19] Nef, *Rise*.

[20] Pounds and Parker, *Coal and steel*; de Vries and van der Woude, *First modern economy*; Unger, 'Energy sources'.

if their efficiency was exceptional or if another input was cheap. (This relationship is the 'factor price frontier' of neoclassical economics.) Coal was that other input that enabled firms to pay a high wage while remaining profitable. Contemporaries were aware of this advantage. Glassmaking was one industry where the French were still ahead of the English in the late eighteenth century. Delaunay Deslandes, the director of Saint-Gobain, was initially sceptical that the English could successfully compete against the French since English wages were one-third higher than French and the standard of living was accordingly superior:

> Given the manner in which the French and English 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.[21]

The burden of high wages in England, however, was offset by cheap energy. In prospectuses of the 1770s, the fuel cost of English glass production was estimated to be only one-sixth of that in France.[22] The same offset occurred in iron production. Richard Reynolds of the Coalbrookdale Iron Company wrote to Earl Gower, President of the Privy Council, in 1784 to object to a proposed tax on coal on the grounds that 'coal . . . is the only article that in any degree compensates for our high price of labour'.[23] The shift from charcoal to coal in industrial processes during the seventeenth and eighteenth centuries—a shift that required the solution of many technical problems—gradually lowered the average price of energy in the English economy and underpinned the rise in the average wage.

The remarks of Deslandes and Reynolds have an important further implication. The high wage in England meant that English workers could buy more food than many of their counterparts abroad. It is conceivable that eating more food might have raised the productivity of English labour, offsetting the high wage and reducing the incentive to mechanize production. However, the import of Deslandes' and Reynolds' comments is that any such increase in productivity was not enough to offset the high wage. Deslandes is particularly compelling since his remarks were not part of a self-interested plea and since he was explicit about the consumption implications of the wages. In his view, the beef and beer enjoyed by the English worker did not compensate his employer for his high wage. English labour was still more expensive than French labour, and the high English wage had to be offset by some other saving. To that we turn.

III

Britain's high-wage, cheap-energy economy was an important determinant of the pace and character of technical change. There were both demand and supply links, and I begin with the former. I emphasize process innovations. Product innovations that imitated Asian trade goods like porcelain and cotton cloth were also impor-

[21] Quoted in Harris, 'Saint-Gobain', p. 67, n. 42.
[22] Ibid., p. 38.
[23] Quoted by Raistrick, *Dynasty*, p. 97.

tant, but their manufacture involved process innovations as well, since production methods had to be redesigned to suit British conditions.[24]

Britain's industrial processes diverged from those used elsewhere 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 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'.[25] Habakkuk used this theory to argue that high wages led Americans to invent labour-saving technology in the nineteenth century.[26] A similar situation obtained in eighteenth-century Britain.[27] It was the prequel to nineteenth-century America.

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 first stage, inspiration, was not the field of action of economics. Today the search for new ideas may be systematic and driven by commercial considerations, but in the eighteenth century exogenous factors probably loomed larger. The ideas incorporated into the inventions of the industrial revolution were either the products of exogenous scientific advances, or acts of genius, or inadvertent by-products of normal operations (learning by doing), or they were copied from other activities.

The second stage of invention was R&D—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 needed 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. 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, and 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, in the case of Abraham Darby II, who discovered how to make wrought iron from coke pig iron—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,

[24] Berg, *Luxury and pleasure.*

[25] Hicks, *Theory*, pp. 124-5.

[26] Habakkuk, *American and British technology.* Economists have since debated how to formalize these ideas (David, *Technical choice*, pp. 19–91; Temin, 'Notes'; Ruttan, *Technology*; Ruttan and Thirtle, *Role of demand*; Acemoglu, 'Factor prices').

[27] Fremdling, 'Continental responses', pp. 168–9, entertains this possibility, as does Mokyr, 'Editor's introduction', pp. 87–9, who also raises many objections to it.

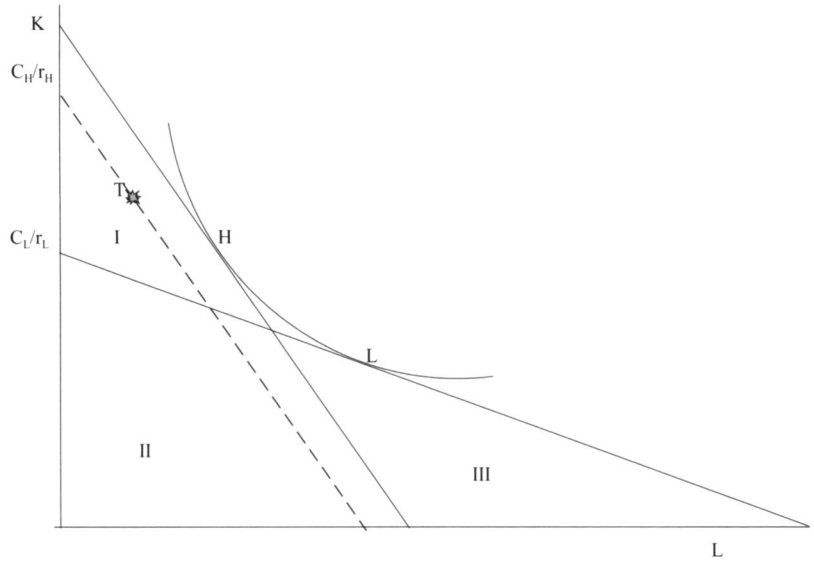

Figure 6. *Biased technical change*
Source: See text.

thus, depended on adoption. Adoption, in turn, depended on factor prices, and that meant that factor prices influenced R&D and hence invention.

We can see how factor prices affected adoption and R&D with a standard isoquant model. The model makes five points: (1) a biased technical change saved one input disproportionately 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, which contrasts high-wage and low-wage firms. 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 firm, and it has a higher capital–labour ratio than the input combination used by the low-wage firm L. 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 in production $C = rK + wN$ and where r and w are the rental price of capital and the wage rate. Each straight line plotted in figure 6 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 firm) 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 C_H/r_H indicates the unit cost of the high-wage firm, and C_L/r_L the cost of the low-wage firm.

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 firm. We know this since a straight line through T that is parallel to the isocost line through H (hence, representing the same w/r) has a lower intersection point on the K axis and, hence, represents lower unit costs. For the low-wage firm, T would raise costs by the same argument. A technology like T is worth using—and thus worth inventing—only for the high-wage firm.

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

The high-wage and the low-wage firms have 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 firms, and that saving generates the demand for the technology, that is, creates a return for someone to invent it. But invention requires R&D 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 over the life of the technology. The total cost line inclusive of R&D costs is $K = C^* + (w/r)N = C/r + (D/q)/r + (w/r)N$, that is, 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 (that is, 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 firm or country paid the R&D costs and the new technology were freely available, it would be adopted because it would cut operating costs. The size of the market affected the profitability of invention through the amortization of R&D costs.[28]

Figure 6 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, such as some well-known technology initiatives of the French state. One was Cugnot's fardier, a steam tractor developed by the military to pull cannons 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.

[28] Acemoglu, 'Factor prices'.

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.[29] These technologies show the force of figure 6 in that they were not profitable to invent because they were not profitable to use.

IV

To apply the model to Britain, we must show that eighteenth-century British inventions were biased towards saving labour and using capital and energy. These biases meant that they were worth using at British factor prices but not at prices prevailing elsewhere.

Thanks to Adam Smith, the pin factory is the most famous production process of the eighteenth century, and this example highlights many of the issues. Smith argued that high productivity was achieved through a division of labour among hand workers.[30] It is very likely that he derived his knowledge from Diderot and d'Alembert's *Encyclopédie*, since both texts divide the production process into 18 stages, and that cannot be a coincidence.[31] Indeed, Smith seems to have used the *Encyclopédie* for the exact purpose that Mokyr suggests—to find out about the latest technology.[32]

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 the mid-eighteenth century.[33] The latter was a well-known tourist destination, and Arthur Young visited it.[34] 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 fly wheels 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'.[35] 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

[29] Doyon and Liaigre, *Jacques Vaucanson*, pp. 144, 214–15, 230–2.

[30] Smith, *Wealth of nations*, pp. 3–12.

[31] Diderot and d'Alembert, eds., *Encyclopédie*, vol. V, pp. 804–7, vol. XXI, pp. 1–8, 'épinglier'. Peaucelle ('Adam Smith et les encyclopédistes'; 'Raisonner sur les épingles'; *Adam Smith*) 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.

[32] Mokyr, *Gifts of Athena*, pp. 68–72.

[33] Hamilton, *English brass*, pp. 103, 255–7.

[34] Russell, *England displayed*.

[35] Young, *Six weeks tour*, p. 138.

factories at the time.[36] 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 possible almost anywhere if you were willing to bear the cost of a steam engine). The Swedish engineer R. R. Angerstein 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.[37] 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.

These considerations operated generally. Much of the technology of the industrial revolution depended on coal. This included many metallurgical applications (for example, using coke to smelt iron and puddling to refine it) and the steam engine, invented by Newcomen in the first decade of the eighteenth century. These technologies all increased coal use relative to other inputs and were only profitable to use at British factor prices. Fremdling, for instance, has shown that British iron making technology was not cost-effective in France and Germany before the middle of the nineteenth century.[38] The Newcomen steam engine was profligate in its use of fuel. Desaguliers, an early enthusiast of steam power, noted that it was only useful where 'coals are cheap' as was the case at Warmley, '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'.[39] Steam engines in the eighteenth century were mainly used in coal mines where coal was effectively free. As a result, they were mainly used in Britain, with Belgium coming a distant second.[40] The coal-using technology was profitable to invent in Britain but not in France or Germany because the low price of coal meant that these techniques were only profitable to use in Britain. They were profitable to use in Belgium, but the small size of the Belgian industry meant that development costs per unit of output were much higher than in Britain, and this consideration militated against carrying out the R&D in Belgium.

The other famous inventions of the industrial revolution were the machines to spin cotton. They were also biased technical changes that raised capital–labour ratios and were profitable to use—hence to invent—only in Britain.[41] Arkwright's water frame was the most far-reaching since it inaugurated factory production. Using 1784 prices to value inputs, the average total cost of 16 count cotton yarn dropped from 35d. per lb when it was produced in the domestic system with hand technology to 28 d. per lb when produced in an Arkwright mill of the period. The

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

[37] Angerstein, *Diary*, p. 138. I thank Martin Dribe for help in deciphering the Swedish stwyfer.

[38] Fremdling, 'Transfer patterns'.

[39] Desaguliers, *Course*, vol. II, pp. 464–5.

[40] Kanefsky and Robey, 'Steam engines', p. 171; Redlich, 'Leaders', p. 122; Tann, 'Makers', pp. 548, 558; Hollister-Short, 'Introduction', p. 22.

[41] The figures discussed in this paragraph and the next are explained more fully in Allen, *British industrial revolution*, pp. 182–216

mill involved mechanical carding as well as spinning, and the system of material flow worked out in Cromford Mill #2. Labour costs fell 8d. per lb, but that saving was offset by a rise in capital costs from about 1d. to 2d. per lb. The capital–labour ratio was almost five times higher with the Arkwight system.

The Arkwright mill was much more profitable in Britain than it would have been in France. In Britain in the late 1780s, cotton mills were built at a cost of about £3 per spindle. In 1784, the water frames in the Papplewick Mill near Nottingham had a rated capacity of 0.125 lbs per 12 hour shift or 37.5 lbs per year assuming they were operated six days per week and 50 weeks per year. Assuming a saving in operating costs of 8d. per lb and a 10-year life for a cotton mill, the rate of return was 40 per cent per year. This was considerably greater than 15 per cent, which investment in fixed capital could realize.[42] The rate of return in France equalled the English rate of return multiplied by the ratio of the English wage relative to the France wage divided by the price of capital in England relative to the price in France. The latter was computed using the prices of iron, copper, and timber. The implied French rate of return was 9 per cent. This calculation probably overstates French profitability since it takes no account of the local supply of 'high tech' components like gears in Lancashire (to be discussed shortly), and their absence in France. The different profit rates explain why there were about 150 large-scale mills operating in Britain in the late 1780s and only four in France. The difference in behaviour does not reflect any difference in ingenuity but rather the choice in England to save the expensive input labour.

When it was invented, British technology was profitable to use only in Britain (or Belgium, in the case of coal). That condition did not persist, however. Inventors modified existing practice to cut costs. This was 'local learning', and it led to the saving of all inputs.[43] In the case of the steam pumping engines, for instance, coal consumption was cut from 44 lbs/hp-hr (horsepower per hour) in 1727 to 2 lbs in 1860 through the efforts of Smeaton, Watt, and Trevethick, as well as by the collective invention carried out by the owners of copper and tin mines in Cornwall.[44] The process of technological improvement in this period was neutral and meant that the steam engine became useful in many activities and places where it had not been practical previously. The culmination of this process was the compound condensing marine engine that allowed steam vessels to displace sailing vessels in voyages between Britain and east Asia.[45] A similar process characterized the cotton spinning industry, where Lancashire engineers halved the capital requirements of Arkwright-style mills as well as cutting labour costs.[46]

These technological developments facilitated the spread of the industrial revolution beyond Britain during the nineteenth century. Figure 7 illustrates the process. Improving technology by modifying existing practice meant that both capital and labour were saved. The trajectory of improvement is represented by the drift of the point representing the new technology from T towards the origin. Initially, the improved versions of the new technique were still profitable to use

[42] Allen, 'Engel's pause', p. 421; C. K. Harley, 'Prices and profits in cotton textiles during the industrial revolution,' Oxford University, discussions papers in economic and social history, no. 81 (2010).

[43] David, 'Common agency contracting'.

[44] Nuvolari, *Making*; idem, 'Collective invention'; idem, 'Making'.

[45] Harley, 'Shift'.

[46] Chapman, 'Fixed capital formation', p. 253.

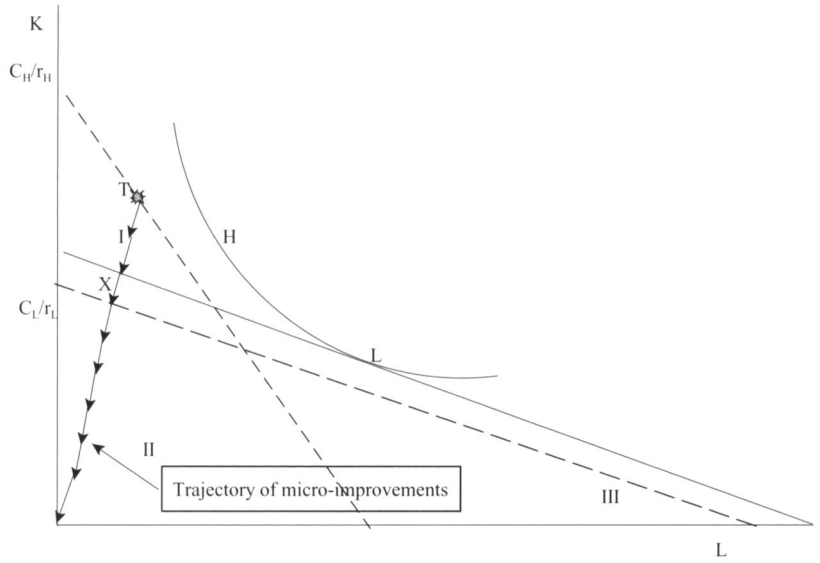

Figure 7. *The trajectory of micro-improvements*
Source: See text.

only in the high-wage economy. This graphical depiction corresponds to the historical stage when Britain was using steam engines, mechanical spinning, and coke smelting, and was, moreover, extending its lead by improving their design. As Britain pulled further ahead, however, other countries continued to ignore the new methods. This 'failure' easily led to accusations of entrepreneurial failure or inadequate engineers, but the real explanation, indicated in figure 7, is that the new technique was still too expensive to use in a low-wage country. Accordingly, a critical juncture is represented by the 'tipping point' where the line from T to the origin crosses the isocost line of the low-wage economy. When that happened, it suddenly became profitable for the low-wage economy to adopt the new technique—indeed, only in its most advanced form. (The new situation is shown graphically by the dotted isocost line parallel to, but below, the original isocost line of the low-wage economy. This new line shows that using a newly discovered input combination below the tipping point reduced costs in the low-wage economy.) Suddenly, the industrial revolution spread beyond Britain in a Gerschenkronian 'great spurt'.

V

The high wages of the British economy in the eighteenth century were an important reason why it was profitable to use—and to invent—labour-saving technology like the spinning jenny. However, there have been other high-wage economies that did not produce such inventions. Fifteenth-century Europe was one example (figure 2). Why was eighteenth-century Britain different? A tempting answer is that the scientific revolution of the seventeenth century led to a greater understanding of the natural world and allowed new technologies to be invented. In terms of figure 6, scientific discoveries created new points like T.

One difficulty with this answer is that the role of science in the industrial revolution was extensively discussed in the 1960s and dismissed by most historians.[47] However, there is a good case for claiming that these historians went too far, and that scientific discoveries underpinned important technology in the industrial revolution. The reason that Hall, for instance, could find no link between scientific discovery and new technology was because he only analysed the period 1760–1830. In the case of Watt, Hall concluded—correctly—that the theory of latent heat contributed nothing important to the invention of the separate condenser. The trouble with this argument is that the scientific discoveries that mattered for the industrial revolution were made before 1700 and not after 1760.

The most important science related to atmospheric pressure, namely, the findings that the atmosphere had weight and that steam could be condensed to form a vacuum.[48] Galileo first considered the problem of why a suction pump could not raise water more than about 10 metres and set his secretary Torricelli to work on it. Torricelli invented the barometer and weighed the atmosphere in 1643. Atmospheric pressure became the hot topic in experimental physics and noteworthy experiments were carried out by Otto von Guericke, Robert Boyle, Robert Hooke, Christiaan Huygens, and Denis Papin. Thomas Savery invented a vacuum pump for draining mines that applied these discoveries. Newcomen applied the same ideas in his steam engine, which was also intended to drain mines. He began working on the problem around 1700, apparently built an engine in Cornwall in 1710, and finally erected his well-known engine at Dudley in 1712. Newcomen could not get a patent in his own right and was forced to do a deal with Savery, whose pump patent was deemed to cover Newcomen's engine. The steam engine was one example of industrial technology derived from science.

A second link from seventeenth-century science involved not only a discovery, but also the active participation of first-class scientists—Christiaan Huygens and Robert Hooke—in the production process. Several inventions relating to timekeeping were involved. The first was the invention of the pendulum clock. Christiaan Huygens proved mathematically that a cycloid was an isochronous curve so that a flexible pendulum restrained between cycloid guides would have a regular swing irrespective of its amplitude. Armed with this insight, he designed the pendulum clock, which dramatically increased the accuracy of timekeeping. Huygens was trying to solve the longitude problem, but the pendulum clock did not work well at sea, so he improvised further. Around 1675, he invented the balance spring, which made an accurate watch possible and, indeed, installed it in a watch. Robert Hooke, the Curator for Experiments of the Royal Society and another scientific luminary, independently conceived of the balance spring perhaps as early as 1660, although he did not apply the idea until he heard of Huygens's work.[49] In themselves, clocks and watches were peripheral to the industrial revolution, but their large-scale production had important spin-offs. The improvements in clock and watch design made them more desirable, and their production grew rapidly. Their moving parts were systems of gears, and each had to be laid out

[47] Landes, *Unbound Prometheus*, pp. 113–14, 323; Mathias, 'Who unbound Prometheus?'; Hall, 'Industrial revolution'.

[48] Landes, *Unbound Prometheus*, p. 104; Cohen, 'Inside Newcomen's fire engine'.

[49] Weiss, *Watch-making*, pp. 111–12.

and cut by hand. Hooke designed the first machine to do this.[50] The growth of the watch industry prompted steady improvement in the design of these machines. The result was the mass production of cheap, accurate gears.

Inexpensive gears revolutionized the design of machinery. Gears replaced levers and belts (as in the spinning wheel) to control, direct, and transmit power. Mills had used gears in this way in the middle ages, but these gears were large, crude, and made of wood. The gears of the industrial revolution were small, refined, and made of brass or iron. Arkwright referred to the gearing in his water frame as 'clockwork' since this system of construction was adapted from clocks and watches. 'Clockwork' was used quite generally to control power in machinery in the nineteenth century, so gearing was the general purpose technology that effected the mechanization of industry.[51]

The watch industry was a key to explaining Arkwright's success and the growth of the cotton industry in Lancashire. Arkwright did not sell water frames; entrepreneurs had to assemble their own engineering departments to construct them. In the late 1780s and early 1790s, the Quarry Bank Mill employed half-a-dozen clock and watch makers over the course of many years to construct the 'clockwork' for the water frames. At the time, there were over 150 Arkwright mills, so on the order of 1,000 of these specialists were employed. Where did they come from? As it happens, most of the world's watch movements were made in one place—southern Lancashire. Landes believed the watch industry was British because the high-wage economy of Britain created a large domestic market for clocks and watches[52]. One reason that cotton production was mechanized in Lancashire (rather than in the Netherlands, for instance) was because the supply of high-quality, cheap gears was far greater there than elsewhere, as was the supply of skilled workmen to assemble them. In addition, the machinery for cutting watch gears was redesigned to produce gears for water frames—first from brass, later from iron. Standardized gears were made by specialist firms and sold to mills.[53] The 'clock work' of the water frame was a spin-off of the watch industry. So we can trace connections from the water frame (and other machinery of the nineteenth century) back to the discoveries of leading scientists, Huygens and Hooke, in the mid-seventeenth century.

VI

Cultural shifts also contributed to the industrial revolution. They increased the quality of would-be inventors and technical personnel, thereby reducing the cost of R&D and increasing the range of projects that were profitable to undertake. There were shifts in both elite culture and popular culture.

Mokyr's model of the industrial enlightenment emphasizes changes in elite culture as a cause of the industrial revolution.[54] On the intellectual plain, the industrial enlightenment refers to the application of the scientific method (experimentation, generalization, mathematization) to the study of technology. 'Most

[50] Ibid., pp. 153–6.
[51] Lipsey, Carlaw, and Bekar, *Economic transformations*.
[52] Landes, *Revolution*, pp. 238–9.
[53] Hills, *Power in the industrial revolution*, pp. 230–49.
[54] Mokyr, *Gifts of Athena*, pp. 28–77.

techniques before 1800 emerged as a result of chance discoveries, trial and error, or good mechanical intuition and often worked quite well despite nobody's having much of a clue as to the principles at work'. The industrial enlightenment changed all that. The scientific study of technology 'would explain the timing of the Industrial Revolution following the Enlightenment and—equally important—why it did not fizzle out like similar bursts of macroinventions in earlier times'.[55]

On the social plain, the industrial enlightenment involved a small number of unusual people working in concert. 'The crucial elements were neither brilliant individuals nor the impersonal forces governing the masses'—for instance, factor price movements like those emphasized here—'but a small group of at most a few thousand people who formed a creative community based on the exchange of knowledge'.[56] At the highest level, information was exchanged at the Royal Society. More people were involved in provincial 'scientific societies, academies, Masonic lodges, coffee house lectures',[57] and similar venues. Individual exchanges were important. When Trevithick invented the high-pressure steam engine, he checked with the mathematician Davies Gilbert to see how much pressure drop he would lose by not including a separate condenser (the answer being one atmosphere).[58]

Mokyr's examples of inventors who 'embodied the Industrial Enlightenment' stand out as cultivated gentlemen committed to science and Enlightenment culture generally. They were active in learned societies. Benjamin Franklin was an archetype. He studied science. He conducted his own experiments, notably those involving electricity. He published his results. He was an inventor (of the lightning rod and bifocals). He corresponded with leading scientists, and he established the America Philosophical Society to advance this kind of work.[59]

Josiah Wedgewood is another example: 'He was, by all accounts, a compulsive quantifier, an obsessive experimenter, and an avid reader of scientific literature'. He was a member of the Royal Society and corresponded with the leading scientists of the day. There were not many people like him: 'It might be objected that Wedgwood was not typical, but the argument of this book is that such unrepresentativeness is the heart of the process of technological change . . . *averages* are . . . not very important: a few critical individuals drive the process'.[60] Other famous exemplars were John Smeaton, James Watt, and Edmund Cartwright.

Britain was different from the US in the social background of its inventors. Khan and Sokoloff found that great British inventors in the period before 1820 were far more likely to come from an elite or professional family than were great US inventors.[61] Many of the Enlightenment figures identified by Mokyr provide examples of this. John Smeaton's father, for instance, was the son of an attorney and attended Leeds Grammar School. James Watt was the son of a merchant, who

[55] Ibid., pp. 32, 39.
[56] Ibid., p. 66.
[57] Mokyr, *Gifts of Athena*, pp. 52–3.
[58] Burton, *Richard Trevithick*, pp. 59–60.
[59] Mokyr, *Gifts of Athena*, pp. 42–3.
[60] Ibid., pp. 52–3.
[61] Z. Khan and K. Sokoloff, 'The evolution of useful knowledge: great inventors, science and technology in British economic development, 1750–1930', Economic History Society Conference, Exeter, 31 March (2007).

was also mayor of Greenock. Watt attended Greenock Grammar School where he studied Latin and Greek. Edmund Cartwright came from a wealthy Northamptonshire family and attended Wakefield Grammar School. Henry Cort's father was a merchant and at one time was mayor of Kendal. Men like this acquired their cultivation, and possibly their enlightened ideas, through their family background and education.[62]

While inventors from advantaged backgrounds were over-represented in Britain compared to the US, Khan and Sokoloff found many British inventors from modest backgrounds. The exemplar of the industrial enlightenment, Josiah Wedgewood, was the son of a potter, who walked seven miles each day to a small school, and was apprenticed to a potter. He acquired his experimental outlook through his own efforts. Many of the great inventors had similar upbringings, although they did not have the intellectual accomplishments of Wedgewood. Richard Arkwright was the son of a poor tailor, attended a night school, and was apprenticed to a barber. James Hargreaves came from a very poor part of Lancashire, was uneducated, and spent most of his life as a hand loom weaver. Samuel Crompton was the son of an unsuccessful farmer and part-time hand loom weaver and attended a local school. As a child, he spun and wove to supplement the family income. Abraham Darby I was the son of a part-time farmer and nailer and was apprenticed to a malt maker. Benjamin Huntsman was the son of a farmer and was apprenticed to a clock maker. Richard Trevithick was educated in a village school, and his father was a copper miner.

Several regularities are striking about these inventors. Firstly, they were brought up in the non-agricultural economy, and indeed their parents (aside from Huntsman) had left agriculture in whole or in part. They were part of the urban or proto-industrial economy. Secondly, none of their parents were labourers. Thirdly, many of them had trade backgrounds. The typical training from someone of that social stratum involved several years in a village school where they learned reading, writing, and arithmetic, followed by an apprenticeship.[63] While we do not have full details on all of these inventors, their formations are consistent with this pattern.

The urban and rural manufacturing economies were created by the commercial success of Britain in the early modern period. In the middle of the eighteenth century, about 55 per cent of the British population was non-agricultural. Along with the Low Countries, England led Europe in this regard.[64] The high-wage economy, of which the inventors were a part, generated the income to purchase the education and training they received. Indeed, literacy rates in north-western Europe were much higher than elsewhere since so many people around the North Sea could afford to send their children to school. Sir Frederick Eden summarized the spending of a labourer in Ealing, and it included 6d. per week to send his six- and eight-year-old sons to school.[65] If the labourer had had to cut back to live on an Italian wage, that expenditure would probably have been eliminated. High wages, town living, a commercial culture, and widespread education constituted a distinctive popular culture that produced inventors.

[62] The biographical details in this and the next few paragraphs are from the new *Dictionary of National Biography*.

[63] Humphries, *Childhood*.

[64] Allen, 'Economic structure', p. 11.

[65] Eden, *State of the poor*, vol. II, pp. 433–4.

The propensity to invent may also have been strengthened as enlightened thinking worked its way down the social hierarchy.[66] Artisans picked up Newtonianism from almanacs, science lecturers, and latitudinarian preaching.[67] One example was John Harrison, the clockmaker, whose chronometer solved the longitude problem. His father was a carpenter and brought him up to the trade; otherwise, he was self-taught. He met the Enlightenment when a clergyman lent him a copy of Nicholas Saunderson's lectures on natural philosophy. Whether this exposure to Newtonianism inclined him to pursue the longitude problem is, of course, one question. Another is how representative he was of artisans in general. Were they exposed to Enlightenment thinking and influenced by it? Presumably, a counterpart to the rise of the mechanical worldview was a decline in belief in witchcraft and magic. There is no consensus among historians of popular culture that such a decline occurred.[68] Sharpe has written that 'Popular scepticism about magic, and popular receptiveness to Newtonian science, are problems which are in urgent need of further research'.[69] In this circumstance, the case for a widespread adoption of the Newtonian worldview must remain conjectural.

How important are the industrial enlightenment and the growth of a literate and numerate class of commercial artisans in explaining the inventions of the industrial revolution? This is a very difficult question to answer for Britain, since the effects of cultural change were intermingled with the powerful incentives created by Britain's unique factor prices to invent labour-augmenting technologies. Supply and demand for R&D were both shifting to encourage invention, so their separate effects are hard to identify. The Continent, therefore, is a more fruitful laboratory for studying the effects of cultural developments, for factor prices there were more stable. Scientific discoveries created some new opportunities for R&D—watch making is an example—but supply factors probably played a larger role. From this perspective, Continental inventions in the seventeenth and eighteenth centuries take on a much greater significance, for they show the effects of culture rather than factor prices or scientific discoveries on the rate of invention.

While Continental history shows that cultural change played a role in stimulating invention, it also highlights the limits to culturally-induced invention. The Dutch economy was a high-wage economy, but it missed the industrial revolution since it lacked cheap coal, a domestic cotton industry, and a watch industry—all of which were crucial in stimulating British invention. France was not a high-wage economy, but the state—animated in part by the Enlightenment confidence that useful technologies could be produced through purposeful activity—financed R&D to develop steam tractors and automatic looms. Without a factor price environment making these techniques cost-effective, they were abandoned. Culture, by itself, could not make up for an inhospitable economic environment.

VII

I have argued that the famous inventions of the British industrial revolution were responses to Britain's unique economic environment and would not have been

[66] Burke, *Popular culture*.
[67] Jacob, *Scientific culture*, pp. 99–115; Stewart, *Rise of public science*; Sharpe, *Early modern England*, p. 329.
[68] Thomas, *Religion*, pp. 767–800; Briggs, *Witches*, pp. 327–30; Burke, *Popular culture*, pp. 274–5.
[69] Sharpe, *Early modern England*, p. 330.

developed anywhere else. This is one reason that the industrial revolution was British. But why did those inventions matter? The French were certainly active inventors, and the scientific revolution was a pan-European phenomenon. Would the French, or the Germans, or the Italians, not have produced an industrial revolution by another route? Were there no alternative paths to the twentieth century?

These questions are closely related to another important question asked by Mokyr: why did the industrial revolution not peter out after 1815? He is right that there were previous occasions when important inventions were made. The result, however, was a one-shot rise in productivity that did not translate into sustained economic growth. The nineteenth century was different—the First Industrial Revolution turned into Modern Economic Growth. Why? Mokyr's answer is that scientific knowledge increased enough to allow continuous invention. Technological improvement was certainly at the heart of the matter, but it was not due to discoveries in science—at least not before 1900. The reason that incomes continued to grow in the hundred years after Waterloo was because Britain's pre-1815 inventions were particularly transformative, much more so than Continental inventions. That is a second reason that the industrial revolution was British and also the reason that growth continued throughout the nineteenth century.

Cotton was the wonder industry of the industrial revolution—so much so that Gerschenkron, for instance, claimed that economic growth in advanced countries was based on the growth of consumer goods industries, while growth in backward countries was based on producer goods.[70] This is an unfortunate conclusion, however, for the great achievement of the British industrial revolution was, in fact, the creation of the first large engineering industry that could mass-produce productivity-raising machinery. Machinery production was the basis of three developments that provide the immediate explanations for the continuation of economic growth until the First World War. Those developments were: (1) the general mechanization of industry, (2) the railroad, and (3) steam-powered, iron ships. The first raised productivity in the British economy itself; the second and third created the global economy and the international division of labour that were responsible for significant rises in living standards across Europe.[71] Steam technology accounted for close to half of the growth in labour productivity in Britain in the second half of the nineteenth century.[72] The application of gears to machinery design had further productivity growth raising effects beyond these.

The nineteenth-century engineering industry was a spin-off of the coal industry. All three of the developments that raised productivity in the nineteenth century depended on two things—the steam engine and cheap iron. Both of these, as we have seen, were closely related to coal. The steam engine was invented to drain coal mines, and it burnt coal. Cheap iron required the substitution of coke for charcoal and was prompted by cheap coal. (A further tie-in with coal was geological—Britain's iron deposits were often found in proximity to coal deposits.) There were more connections: the railroad, in particular, was a spin-off of the coal industry. Railways were invented in the seventeenth century to haul coal in mines and from

[70] Gerschenkron, *Economic backwardness.*
[71] O'Rourke and Williamson, *Globalization.*
[72] Crafts, 'Steam'.

mines to canals or rivers. Once established, railways invited continuous experimentation to improve road beds and rails. Iron rails were developed in the eighteenth century as a result, and alternative dimensions and profiles were explored. Furthermore, the need for traction provided the first market for locomotives. There was no market for steam-powered land vehicles because roads were unpaved and too uneven to support a steam vehicle (as Cugnot and Trevithick discovered). Railways, however, provided a controlled surface on which steam vehicles could function, and colliery railways were the first purchasers of steam locomotives. When George Stephenson developed the Rocket for the Rainhill trials, he tested his design ideas by incorporating them in locomotives he was building for coal railways. In this way, the commercial operation of primitive versions of technology promoted further development as R&D expenses were absorbed as normal business costs.

Cotton played a supporting role in the growth of the engineering industry for two reasons. The first is that it grew to an immense size. This was a consequence of global competition. In the early eighteenth century, Britain produced only a tiny fraction of the world's cotton yarn and cloth. The main producers were in Asia. As a result, the price elasticity of demand for English cotton cloth was extremely large. If Britain could become competitive, it could expand production enormously by replacing Indian and Chinese producers. Mechanization led to that outcome.[73] The result was a huge industry, widespread urbanization (with such external benefits as that conveyed), and a boost to the high-wage economy. Mechanization in other activities did not have the same potential. The Jacquard loom, a renowned French invention of the period, cut production costs in lace and knitwear, and thereby induced some increase in output. However, knitting was not a global industry, and the price elasticity of demand was only modest, so output expansion was limited. One reason that British cotton technology was so transformative was that cotton cloth was a global industry with more price-responsive demand than other textiles.

The growth and size of the cotton industry in conjunction with its dependence on machinery sustained the engineering industry by providing it with a large and growing market for machinery. The history of the cotton industry was one of relentlessly improving machine design—first with carding and spinning and later with weaving. Improved machines translated into high investment and demand for equipment. By the 1840s, the initial dependence of cotton manufacturers on water power gave way to steam-powered mills.[74] By the middle of the nineteenth century, Britain had a lopsided industrial structure. Cotton was produced in highly mechanized factories, while much of the rest of manufacturing was relatively untransformed. In the mid-nineteenth century, machines spread across the whole of British manufacturing (one of the causes of the continuing rise in income). Until then, cotton was important as a major market for the engineering industry.

The reason that the British inventions of the eighteenth century—cheap iron and the steam engine, in particular—were so transformative was because of the possibilities they created for the further development of technology. Technologies invented in France—in paper production, glass, and knitting—did not lead to general mechanization or globalization. One of the social benefits of an invention

[73] S. Broadberry and B. Gupta, 'Wages, induced innovation and the great divergence: Lancashire, India and shifting competitive advantage in cotton textiles, 1700–1850', rev. version, CEPR discussion paper 5183 (2006).
[74] von Tunzelmann, *Steam power*, pp. 175–225.

is the door it opens to further improvements. British technology in the eighteenth century had much greater possibilities in this regard than French inventions. The British were not more rational or prescient than the French in developing coal-based technologies: the British were simply luckier in their geology. The knock-on effect was large, however. There is no reason to believe that French technology would have led to the engineering industry, the general mechanization of industrial processes, the railway, the steam ship, or the global economy. In other words, there was only one route to the twentieth century—and it traversed northern Britain.

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