

The British Industrial Revolution in Global Perspective:
How Commerce Created
The Industrial Revolution and Modern Economic Growth

by

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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 renown¹, for they mark the start of a process that has carried the West, at least, to the mass prosperity of the twenty-first century. The purpose of this essay is to explain why they occurred in the eighteenth century, in Britain, and how the process of their invention has transformed the world.

The last sentence introduces an important theme of this essay, which is the Britishness of the industrial revolution. Until recent decades, this was axiomatic: The industrial revolution started in Britain with the inventions that created factory textile production, the shift to coal and coke in the iron industry, and the perfection of the steam engine. Economic growth on the continent occurred when these innovations were adopted there. This schema was first called into question by national income studies which indicated that the pace of economic growth in France was not very different from that in England despite the differences in economic structure—hence, the thesis of O'Brien and Keyder (1978) that there were “two paths to the twentieth century.” This critique has gathered force with the recent emphasis on the Scientific Revolution, a pan European phenomenon, as the cause of the Industrial. While these contributions broaden our understanding of the industrial revolution, it is our contention that it really was fundamentally British.

Explaining the industrial revolution is a long standing problem in social science, and all manner of prior events have been adduced as causes (Hartwell 1967, Mokyr 1999). The role of political structure—parliamentary checks on the executive, the security of property rights, the flexibility of the legal system—is at the centre of much current discussion. According to this view, the dramatic changes of the late eighteenth century can be traced back to the Glorious Revolution of 1688 that consolidated parliamentary ascendancy, minimal government, and secure property rights. Supposedly, these legal changes created a favourable climate for investment that made the industrial revolution possible (North and Weingast 1989, De Long and Schleifer 1993, LaPorta, Lopez-de-Silanes, Schleifer, Vishny 1998, Acemoglu, Johnson, and Robinson 2005). This interpretation, however, has some weaknesses: Studies of banking and interest rates fail to detect any structural break after 1688, so the improved investment climate is not manifest in anything financial (Clark 1996, Epstein 2000, Quinn 2001). Property rights were at least as secure in France—possibly, in China for that matter—as in England (Hoffman, Postel-Vinay, Rosenthal 2000, Pomeranz 2000). Indeed, one could argue that France suffered because property was too secure: Profitable irrigation projects were not undertaken in Provence because France had no counterpart to the private acts of the British parliament that overrode property owners opposed to the enclosure of their land or the construction of canals or turnpikes across it

¹There has been a debate about the breadth of technological progress during the industrial revolution with Crafts (1985), Harley (1999), Crafts and Harley (1992, 2000) arguing that productivity growth was confined to the famous, revolutionized industries in the period 1801-31, while Temin (1997) has argued that many more industries experienced productivity growth. Whatever one believes about 1801-31, it is clear that many non-revolutionized industries experienced productivity growth between 1500 and 1850. The incentives to invent discussed in this paper applied to all industries, not just the famous ones I discuss here.

(Rosenthal 1990, Innes 1992, 1998, Hoppit, Innes, Styles 1994). The Glorious Revolution meant that “despotic power was only available intermittently before 1688, but was always available thereafter” (Hoppit 1996, p. 126). Finally, taxes were higher in Britain than across the Channel (Mathias and O’Brien 1976, 1978, Hoffman and Norberg 1994, Bonney 1999). In any event, it was a long stretch from the excise tax on beer or the cost of foreclosing on a defaulting mortgagor (not actually a cheap process in eighteenth century England) to Watt’s invention of the separate condenser. An explanation of the technological breakthroughs has to be more focussed on technology than is usual in constitutional discussions.

The industrial revolution was fundamentally a technological revolution, and progress in understanding it can be made by focussing on the sources of invention. This subject has been opened up for economists by the researches of Joel Mokyr (1990, 2002), and I will examine his views on macroinventions, the scientific revolution, and the industrial enlightenment. While Mokyr takes us forward by emphasizing the social context in which invention occurred and the importance of information flows, we can sharpen our understanding by concentrating on the incentives faced by inventors and the context in which they worked. This approach indicates that the reason the industrial revolution happened in Britain, in the eighteenth and nineteenth centuries, was not because of luck (Crafts 1977) or British genius or culture or the rise of science. Rather it was Britain’s success in the international economy that set in train economic developments that presented Britain’s inventors with unique and highly remunerative possibilities. The industrial revolution was a response to the opportunity.

What commercial success did for Britain was to create a structure of wages and prices that differentiated Britain from the continent and, indeed, Asia: In Britain, wages were remarkably high and energy cheap. This wage and price history was a fundamental reason for the technological breakthroughs of the eighteenth century whose object was to substitute capital and energy for labour. Scientific discoveries and scientific culture do not explain why Britain differed from the rest of Europe. They may have been necessary conditions for the industrial revolution, but they were not sufficient: Without Britain’s distinctive wage and price environment, Newton would have produced as little economic progress in England as Galileo produced in Italy.

There were, however, important features of British popular culture that distinguished the country from much of the continent, and those features—greater literacy and numeracy—underpinned the technological achievements of the eighteenth century. They were not autonomous movers, however, but were themselves consequences of the economic development that preceded the industrial revolution and that produced the high wage, cheap energy economy. Underlying the technological breakthroughs of the industrial revolution was Britain’s commercial and imperial expansion of the seventeenth and eighteenth centuries, which was the cause of the peculiar wage and price pattern. The state policies that mattered most were Mercantilism and Imperialism.

The working assumption of this paper is that technology was invented by people in order to make money. This idea has important implications. First, inventions were investments where future profits had to offset current costs. The technical discoveries were either new products or reductions in the cost of making existing products. In either case, the profitability calculation governing invention depended on the prices of the products and the prices of the various inputs. As we will see, labour was particularly expensive and energy particularly cheap in Britain, so inventors in Britain were led to invent machines that substituted energy and capital for labour. Second, the balance between the profits and the

costs of an invention depended on the size of its market. The scale of the mining industry in eighteenth century Britain was much greater than anywhere else, so the return to inventing improved drainage machinery (a.k.a. the steam engine) was greater in Britain than in France or China. Third, patents that allow the inventor to capture all of the gains created by his invention raise the rate of return and encourage invention. Indeed, North and Thomas (1973) have argued that it was better property rights for knowledge that explain the inventions of the industrial revolution. However, the English patent law was enacted in 1624 and attracted little interest for much of the seventeenth century, so the explanation of the inventions of the eighteenth turns on the greater incentive to invent rather than on a change in law that met an existing, latent demand for patenting.² Fourth, in the absence of patents, the incentive to invent was limited to the gains the inventor could realize in his own firm, and these were likely to have been small. Firms could increase the return to inventing by learning from each other. In that case, they divided the costs and pooled the gains. Indeed, collective invention was important before private invention took off in the eighteenth century and has remained a complement to the present day (Allen 1983, Epstein 1998, 2004, Nuvolari 2004a, 2004b).

Britain—a high wage, cheap energy economy

Since invention was an economic activity, its pace and character depended on factors that affected business profits including, in particular, input prices. Why the industrial revolution happened in eighteenth century Britain is easier to understand 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 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:

1. At the exchange rate, British wages were higher than those of its competitors.
2. High silver wages translated into higher living standards than elsewhere.
3. British wages were high relative to capital prices.
4. 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. The typical price history is based on the archives of an institution that lasted for hundreds of years—colleges and hospitals are favourites. The historian works through their accounts recording the quantity and price of everything bought or sold and draws up tables of the annual averages. Usually prices are found for a range of agricultural and food stuffs as well as cloth, 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

²On the operation of the English patent system, recent research includes: Dutton (1984), MacLeod (1986, 1988), Nuvolari (2004a), Khan (2005), Khan and Sokoloff (2006).

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.

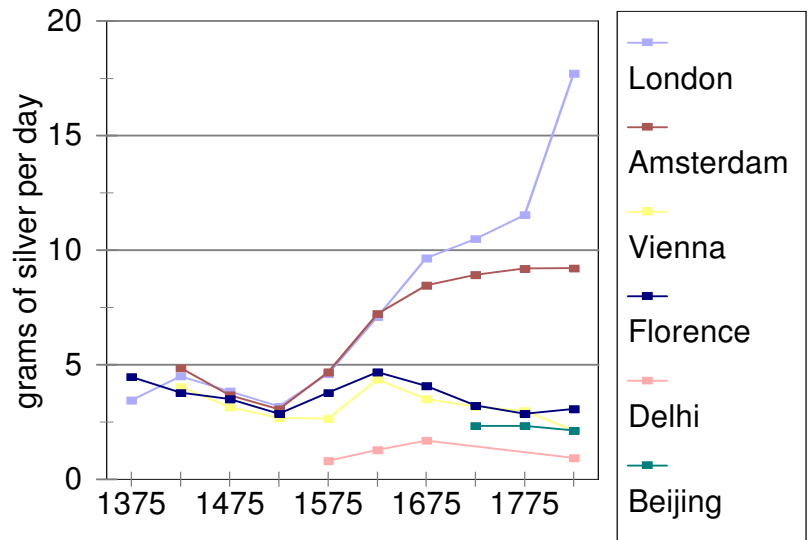
The various units of account in which the data were recorded have been converted to grams of silver since silver coins were the principal medium of exchange. The figure shows that the divergence in nominal wages was minimal in Europe at the end of the late middle wages. There was little wage inflation 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, 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 builder's 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 (Gilboy 1934, Allen 2001, 2003).

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 northwest of the continent (Özmucur and Pamuk 2002, Allen 2005, Allen, Bassino, Ma, Moll-Murata, van Zanden 2005, cf. Allen, Bengtsson, Dribe 2005).

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 to be full time annual earnings³ divided by the cost

Figure 1
Labourers' wages around the world



³European 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.

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 (e.g. oats in northern Europe, polenta in Florence, sorghum in Beijing, millet in Delhi). Very small portions of meat, peas or beans, butter or oil, cloth, fuel, and housing are also included. Consumption is set at the low level of 1920 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

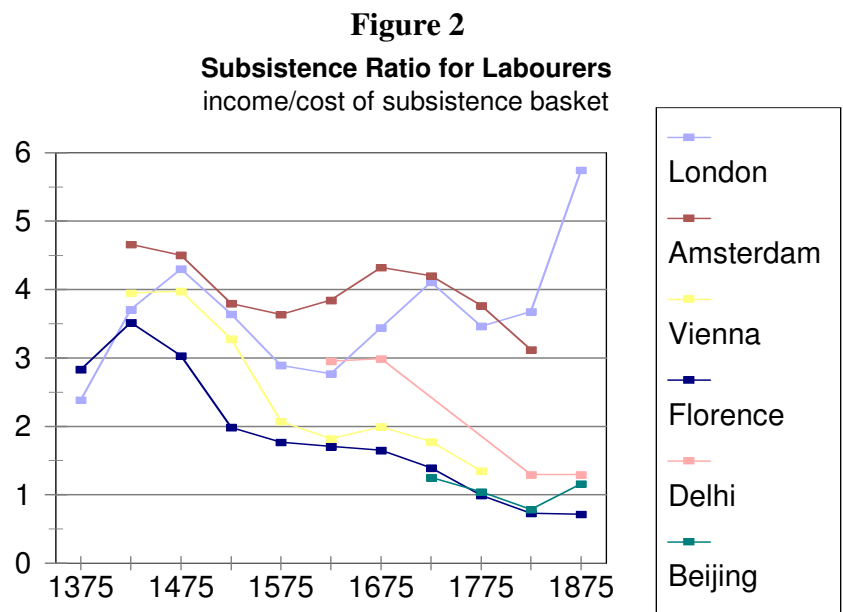
that real incomes were high everywhere in the fifteenth century. Welfare ratios in London and the Low Countries were trendless across the early modern period, although there were oscillations in the series.

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 century (Shammas 1990,

McKendrick, Brewer, and Plumb 1982, de Vries 1993, Fairchilds 1993, Weatherill 1996, Berg and Clifford 1999, Berg 2005). 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 along 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% 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 spend was directed towards basic necessities.

Many Asian wages are based on monthly earnings, and I assume employment for twelve months.



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% more than that standard. Craftsmen in northwestern 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 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.

The ratio of the wage relative to the price of capital was trendless and similar in all cities from 1550 to 1650. 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 different trajectories of the wage-rental ratio created different incentives to mechanize production in the two parts of Europe. In England, the continuous rise in the cost of labour relative to capital led to an increasingly greater incentive to invent ways of substituting capital for labour in production. On the continent, the reverse was true: Factor price movements led businesses to search for ways of substituting increasingly cheap labour for capital. It was not Newtonian science that inclined British inventors and entrepreneurs to seek machines that raised labour productivity but the rising cost of labour.

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 bar graph of the ratio of the building wage rate to the price of energy in the early 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

Figure 3

Wage Relative to Price of Capital

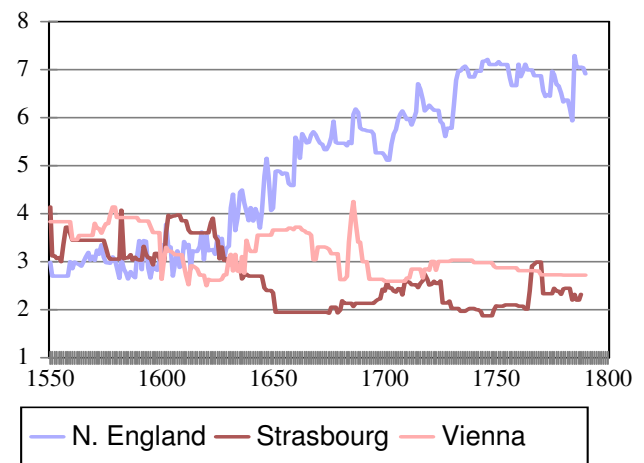
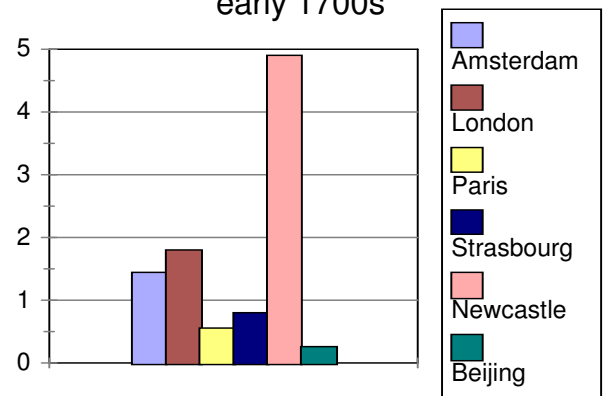


Figure 4

Price of Labour relative to Energy early 1700s



expressed as grams of silver per million BTUs. The ratio is calculated for the cheapest fuel available in each city—coal in London and Newcastle, peat in Amsterdam, charcoal or fire wood 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 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. 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.

Why were British wages and prices unique?

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 northwestern 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 woolen clothes 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 (O'Brien 2006). 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 10,000 people increased from 7% to 29%. The share of the workforce in agriculture dropped from about 75% to 35%. 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 (Acemoglu, Johnson, Robinson 2005, Wrigley 1987, O'Brien 1999, Ormrod 2003, Allen 2000, 2003).

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 (Jevons 1865, Neff 1932, Hatcher 1993, Smil 1994, Pomeranz 2000, Sieferle 2001), and Wrigley (1988) put it on the modern research agenda. 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 coal fields. 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 brought down internal shipping costs. Except perhaps for southern Belgium, no region anywhere in the world had the same combination of large population and cheap energy. Belgian coal output, however, was only 3% of Britain's in 1800, and the return from inventing coal using technology was correspondingly reduced.

Cheap fuel was important for two reasons. First, 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.

Second, coal is a 'natural' resource, but the coal industry was not a natural phenomenon. Some coal was mined in the middle ages (Hatcher 1993). 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 fire wood 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. 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, sulfur 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 per BTU as coal (Figure 6). That differential made it worthwhile for buyers to figure out how to substitute coal for wood—in fact, a difficult problem (Nef

Figure 5

**Price of Energy
early 1700s**

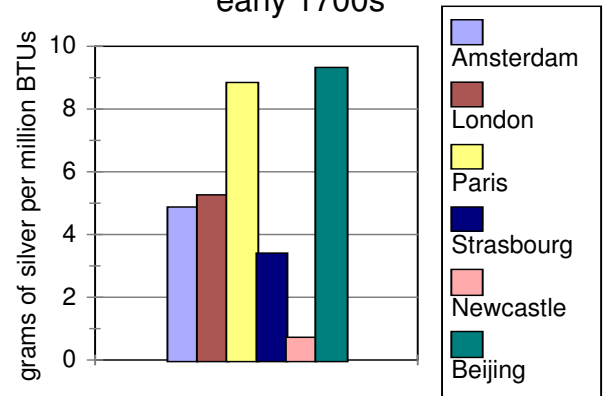
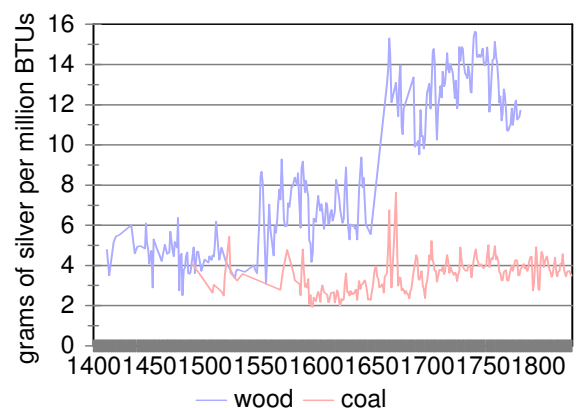


Figure 6

Real Prices of Wood & Coal in London



1932)–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 were 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 (Pounds and Parker 1957, de Vries and van der Woude 1997, Unger 1984). The coal deposits that stretched from northeastern France across Belgium and into Germany were as useful and accessible as Britain’s. With the exception of the mines near Mons and Liège, they were 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.

Why Britain’s unique wages and prices mattered: Substituting Capital for Labour

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. In analyzing these, it is useful to distinguish between product and process innovations, for they were influenced by different features of the price structure.

Historians of consumption have emphasized product innovations as a cause of the industrial revolution (Berg 2005). Trade with Asia brought new products to Britain–cotton fabrics, Chinese porcelain, coffee and tea. Britain’s high wages meant that the demand for these goods was not confined to the middle classes but included skilled workers and even labourers, so the market was far broader than in much of Europe. British manufacturers attempted to make these goods or imitations of them in order to meet that demand. Cotton textiles is a famous example we will consider later. There was also much product innovation in porcelain as English manufacturers (Wedgwood is the most famous) developed materials and designs that could compete with the Chinese (Young 1999). To an important extent, the industrial revolution was an exercise in import substitution.

Process innovations were important in their own right, and much of the product innovation also involved redesigning production processes to suit British conditions. What mattered was the wage of labour relative to the prices of capital and energy. 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-labour ratios. 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.” Habakkuk (1962) used this insight to argue

that high wages led Americans to invent labour saving technology in the nineteenth century, and a similar situation obtained in eighteenth century Britain.⁴ Economists have since debated how to formalize these ideas (David 1975, pp. 19-91, Temin 1971, Ruttan 2001, Ruttan and Thirtle 2001, Acemoglu 2003). One problem is that businesses are only concerned about costs *in toto*—and not about labour costs or energy costs in particular—so all cost reductions are equally welcome. I will not review the debate here. Instead, I will show that invention in the British Industrial Revolution was consistent with Hick’s observation, while the subsequent perfection of technology looks more like a neutral process. The following generalizations apply to many inventions including the most famous:

1. The British inventions were biased. They were labour saving and energy and capital using.

Thanks to Adam Smith, the pin factory is the most famous production process of the eighteenth century. 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.⁵ Indeed, Smith seems to have used the *Encyclopédie* for the exact purpose that Mokyr 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 practise 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 midcentury. (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 powered 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.” (Young 1771, 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.⁶ Arthur Young observed that the Warmley works “are very well worth seeing.” It is a pity that Adam

⁴Fremdling (2004, pp. 168-9) entertains this possibility, as does Mokyr (1993, pp. 87-89), who also raises many objections to it.

⁵Peaucelle (1999, 2005, 2006) 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.

⁶Early eighteenth century water-driven scouring machinery is still in operation and can be seen at the Forge Mill Needle Museum, Redditch.

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 (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 'stfwer' per bushel," which was about half the Newcastle price.⁷ 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.

2. As a result of 1, cost reductions were greatest at British factor prices, so the new technologies were adopted in Britain and not on the continent.

One of the big themes in the history of the industrial revolution is the lag in adopting British technology on the continent. There has been a tendency to regard the inventions of the industrial revolution as such marvellous improvements that only a fool would ignore them. Coke smelting is an important example, and Landes (1969, pp. 216, 528) attributed its slow diffusion on the continent to entrepreneurial failure. However, a close study of the economics shows that coke smelting was not profitable in France or Germany before the mid-nineteenth century (Fremdling 2000). Continuing with charcoal was rational behaviour in view of continental factor prices. This result looks general; in which case, adoption lags mean that British technology was not cost-effective at continental input prices.

3. The famous inventions of the industrial revolution were made in Britain rather than elsewhere in the world because the necessary R&D was profitable in Britain (under British conditions) but unprofitable elsewhere.

Research and development was expensive, and it was fundamental to inventing in the eighteenth century. Consequently, inventions were undertaken only when the R&D benefits exceeded the costs. If the French or Germans did not adopt an invention when it was freely available, then it brought them no benefit, and there would have been no point in expending resources to have invented it. If we ask why coke smelting, or the spinning jenny, or the steam engine were invented in Britain rather than in China or France, the adoption lags imply that the rates of return to these R&D projects were zero outside Britain. To understand invention, we do not have to entertain the arcane questions that arise in cultural discussions of the topic: Did Chinese science have a sufficiently developed concept of the vacuum to allow the conceptualization of the low pressure steam engine? Was French engineering theoretically inclined while British was empirical? The answer lies in different economic conditions that led different countries to invent different kinds of technology.

4. Once British technology was put into use, engineers continued to improve it, often by economizing on the inputs that were cheap in Britain. This made British technology cost-

⁷I am thank Martin Dribe for help in deciphering the Swedish stwyfer.

effective in more places and led to its spread across the continent later in the nineteenth century.

As British technology evolved, capital and energy intensities declined. Chapman (1970, p. 253) observed that “the mechanical genius of Lancashire was directed towards a reduction of plant costs, which fell from £2 per spindle at the height of the Arkwright era to less than £1 a spindle by 1836.” It was the same story with steam power: The first Newcomen engines were profligate in their use of fuel. Smeaton improved them in the mid-eighteenth century cutting the use of coal. Watt’s separate condenser saved more fuel. The high pressure steam engine, and the Cornish engine reduced energy use much further (Nuvolari 2004a). By the mid-nineteenth century, steam engines could be used in France even though coal was expensive since they did not use much of it. The culmination of this process was compound condensing marine engines that finally made steam ships cheaper than clipper ships on the very long routes from the Pacific to Britain (Harley 1971).

Three idealist explanations

The theory advanced here explains the technological breakthroughs of the industrial revolution in terms of the economic base of society—natural resources, international trade, profit opportunities. Through their impact on wages and prices, these prime movers affected both the demand for technology and its supply. An alternative approach traces the inventions of the industrial background back to the realm of ideas and culture. This view is advanced by cultural historians like Margaret Jacob (1988, 1997) and Larry Stewart (2004) and by economists like Joe Mokyr (2002). His writings have been highly influential in putting technological history at the centre of debate and in emphasizing the importance of networks and communication channels for understanding invention. However, the history of wages and prices as well as the detailed investigation of famous inventions (to be considered shortly) both suggest that economic evolution exerted a stronger influence on invention than autonomous changes in culture or ideas.

There are three distinct idealist explanations of the industrial revolution that need to be considered:

1. The technological breakthroughs were ‘macro-inventions,’ i.e. acts of genius or serendipity rather than responses to economic incentives.
2. The technological breakthroughs were applications of scientific discoveries that were made for scientific rather than economic reasons.
3. The industrial revolution was the result of the spread of scientific culture that made people more experimental, more numerate, and more systematic in their study of technology. This cultural change was due to the success and example of Newtonian science.

These possibilities affected the supply of technology rather than its demand. The first two increased the supply of technology by providing engineers with Big Ideas to develop. The third improved the ability of engineers to turn ideas into commercial applications.

Consider macro-inventions first. These differ from micro-inventions, which are “the small incremental steps that improve, adapt, and streamline existing techniques already in use, reducing costs, improving form and function, increasing durability, and reducing energy and raw material requirements.” Microinventions are “more or less understandable with the help of standard economic concepts. They result from search and inventive effort, and

respond to prices and incentives.” In contrast, macroinventions embody “a radical new idea, without clear precedent” and emerge “more or less *ab nihilo*.” They “do not seem to obey obvious laws, do not necessarily respond to incentives, and defy most attempts to relate them to exogenous economic variables. Many of them resulted from strokes of genius, luck or serendipity” (Mokyr 1990, p. 13.) Mechanical spinning is a pre-eminent example. (Mokyr 1993, p. 20).

Stress on pure genius is hard to square with my discussion of wages, prices, and the incentives they created for inventing technology, for that analysis treats all of the inventions of the industrial revolution as micro-inventions. Which were they: micro or macro? The tests are: (a) to see whether mechanical spinning, for instance, emerged ‘*ab nihilo*’ or whether it was a development of existing ideas and (2) to see whether its ‘invention’ involved a development program that made sense in terms of economic opportunities. When we perform these tests, we see that the famous inventions of the industrial revolution look more like micro-inventions than macro-inventions.

How about scientific discovery as a source of eighteenth century technology? This is a favourite theme of university presidents and vice chancellors, and, indeed, has been argued by proponents of scientific research since the seventeenth century. In 1671, Robert Boyle developed the argument. “Inventions of ingenious heads doe, when once grown into request, set many Mechanical hands a worke, and supply Tradesmen with new meanes of getting a liveleyhood or even inriching themselves.” There were three ways by which “naturalists” could improve technology. “The first [was] by increasing the number of Trades, by the addition of new ones.” The pendulum clock and scientific instruments were Boyle’s examples. “The second [was] by uniteing the Observations and Practices of differing Trades into one Body of Collections,” so that techniques used in one trade could be transferred to another. “And the third [was] by suggesting improvements in some kind or other of the Particular Trades.” Cornelius Drebbel’s invention of turkey red dye was an example, but what particularly excited Boyle were the possibilities of inventing “engines” to mechanize production. “When we see that Timber is sawd by Wind-mills and Files cut by slight Instruments; and even Silk-stockings woven by an Engine...we may be tempted to ask, what handy work it is, that Mechanicall contrivances may not enable men to performe by Engines.” Boyle thought that there were more possibilities here “than either Shopmen or Book men seem to have imagined” and experimental scientists would discover them. (Boyle 1671, Essay 4, pp. 10, 20.)

Was Boyle right? The impact of scientific discovery on technology was explored thoroughly in the 1960s (Musson and Robinson 1969, Mathias 1972). The search turned up only one important application of scientific knowledge to industry—the steam engine, which was based on the discovery that the atmosphere has weight. It is a big leap, however, from that connection to the conclusion that the discovery of the weight of the atmosphere *caused* the invention of the steam engine. I will examine its history and argue that it was only in Britain that the economic benefits were great enough to justify the expense of perfecting the steam engine. No one would have found it worthwhile anywhere else in the world. Its invention was as much a response to economic opportunities as to scientific advance. And apart from the steam engine, there’s not many applications that can be linked to science.

The third idealist explanation is the most amorphous. The basic idea is that the scientific revolution created a ‘culture of science’ that led to the inventions of the industrial revolution. The explanation is usually developed in two stages. The first stage explains why the industrial revolution happened in Europe at the end of the eighteenth century (rather than

in China or in the middle ages); the second explains why it happened in Britain rather than France.

Mokyr (2002, p. 29) gives a succinct statement of the first stage claim.

I submit that the Industrial Revolution's timing was determined by intellectual developments, and the true key to the timing of the Industrial Revolution has to be sought in the scientific revolution of the seventeenth century and the Enlightenment movement of the eighteenth century. The key to the Industrial Revolution was technology, and technology is knowledge.

Mokyr coined the term Industrial Enlightenment to describe the features of the Enlightenment that linked the Scientific Revolution of the seventeenth century to the Industrial Revolution of the eighteenth and nineteenth. The Industrial Enlightenment emphasized the application of the scientific and experimental methods to the study of technology, the belief in an orderly universe governed by natural laws that could be apprehended by the scientific method, and the expectation that the scientific study of natural world and technology would improve human life. These ideas were popularized until they eventually permeated the culture. The channels through which this was done included professional scientific societies like the Royal Society, and the publication of books like the *Encyclopédie* that described manufacturing processes (although the tale of pin-making gives us pause). Popular scientific societies and lectures also played a role in disseminating the new approach to technology and nature.

According to Mokyr (2002, p. 29), the industrial enlightenment explains “why the Industrial Revolution took place in western Europe (although not why it took place in Britain and not in France or the Netherlands.)” This must be so when the pre-eminent example of knowledge diffusion is Diderot and d’Alembert’s *Encyclopédie*. Britain’s lead over France is attributed to a difference in the engineering cultures of the two countries: The French were supposedly theoretical, while the British were practical. This is the second stage claim.

With a theory so multi-faceted, it is hard to reach a definitive judgement: The theory stimulates, but there are many grounds for reservation. The theory posits European and national cultures that make little allowance for class or social status differences in attitudes. What exactly were the links between Cambridge dons like Newton and artisan inventors like Abraham Darby or James Hargreaves? This problem was apparent to eighteenth century writers. In The Fable of the Bees, Mandeville (1724) remarked:

They are very seldom the same Sort of People, those that invent Arts, and Improvements in them, and those that enquire into the Reason of Things: this latter is most commonly practis’d by such, as are idle and indolent, that are fond of Retirement, hate Business, and take delight in Speculation: whereas none succeed oftener in the first, than active, stirring, and laborious Men, such as will put their Hand to the Plough, try Experiments, and give all their Attention to what they are about.

To close the gap between high science and artisan technology, the culturalists propose coffee houses giving popular science lectures. Who attended these events and what they heard are less than clear. The minutes of the Chapter Coffee House society, which met between 1780 and 1787, have been published (Levere and Turner 2002), and they provide a rare peek inside. They warrant attention since the history of the society provides “hard

evidence of the interplay between science and technology, and industrial revolution.” But does it? 60% of the 55 members were Fellows of the Royal Society and only five had a connection to manufacturing. Of those five, only one ever attended a meeting. The Chapter Coffee House was not science communicating with industry. It was science talking to itself. There probably were some occasions when high science addressed the hoi polloi, but the suspicion must be that Mandeville was right: these were separate spheres.

More suspicion that the Industrial Enlightenment was mainly an upper class cultural phenomenon with little relation to production comes from the study of its twin—the Agrarian Enlightenment. This involved many of the same themes as the Industrial Enlightenment—except applied to farming rather than manufacturing—and, indeed, many of the same people, once returned to their country houses at the close of the London season. These were the celebrated improving landlords of England, who enclosed their estates, turned their home farms into experimental stations, patronized Arthur Young (a great collector of farming data), published reports of new crops and cultivation methods, and promoted improved farming among their tenants. This was the enlightenment project applied to agriculture, but, unfortunately for the cultural theory, it had little effect on agricultural productivity (Wilmot 1990). The impact of the Agrarian Enlightenment was inherently limited because it was a movement among the gentry and aristocracy, not among the farmers who actually tilled the land. The books were written by landlords, for landlords. The King could play at being Farmer George, but there was little connection with real production. Was the Industrial Enlightenment as ineffective?

It is important to distinguish between popular culture and elite culture and ask how they were related. Cultural historians see popular culture changing in response to high science, an elite cultural activity. In contrast, I contend that popular culture evolved in response to changes in the economy. The growth of international trade led to much greater urbanization in northwestern Europe. Jobs in trade, manufacturing, and commerce required skills that agriculture had not demanded. Literacy rates in medieval Europe were much higher in cities than in the countryside for this reason, so literacy rose with urbanization. The high wage economy of the commercial centres also aided the accumulation of human capital by making it easier for people to pay for education and knowledge. Beyond that, the invention of printing sharply reduced the price of books leading to much greater effective demand for both useful knowledge and pleasure (van Zanden 2004a, 2004b, Reis 2005). The same factors probably boosted numeracy (Thomas 1987). Knowledge of arithmetic and geometry was important to keep accounts and navigate ships. In his path breaking epidemiological study of London, Graunt (1662, p. 7) attributed his calculations not to science but to trade: “It depends upon the *Mathematiques* of my *Shop-Arithmetic*.” The much greater level of human capital in the eighteenth century than in the middle ages is an important reason why the industrial revolution did not happen earlier.

Do differences in human capital explain why the industrial revolution occurred in Britain rather than France? Literacy in France as a whole was lower than in Britain, but France was a bigger country with a larger population and considerable diversity. Literacy in northern France was about as common as in Britain, and so human capital differences may not have been important. Indeed, it is not clear that there was much difference in inventiveness between eighteenth century Britain and France. There are certainly many examples of the French inventing. Why do we think the British had a more pragmatic engineering culture than the French? Because it was Brits who first smelted iron with coke, invented the steam engine, and discovered how to spin with machines. In the rest of this

essay, I will show that these differences in behaviour were due to differences between the countries in the profitability of doing R&D. If that argument is accepted, then cultural explanations become superfluous.

Some famous inventions

The only way to adjudicate between the cultural and economic explanations of technical change is to test them against the history of invention. I will examine three famous inventions—coke smelting, mechanical spinning, and the steam engine. I explore four themes:

- What was the origin of the idea embodied in the invention? Was it an inspired act of genius or a scientific discovery? With the exception of the steam engine, which was based on science, the fundamental insight was copied from other activities. Boyle proposed the publication of craft knowledge to promote invention-by-copying, and Mokyr has made it part of his Industrial Enlightenment. Indeed, copying was the general pattern and shows that the Industrial Revolution was based on little ideas—not big ideas as often assumed.
- What technical problems had to be solved in order to put the idea into practice? How much R&D was involved in making the idea work? R&D was the crux of invention in the eighteenth century, and all of the famous inventions including Newcomen's steam engine, required substantial development programs to perfect them. These R&D projects exhibited the modern trilogy of development costs, external finance, and patenting. The expense of R&D turned invention from a scientific into an economic activity.
- How were these inventions related to Britain's unique wages and prices? Were the inventions biased in the sense that they cut costs more at British prices than at foreign prices? All of these inventions make sense in terms of the high wages and cheap coal of the British economy. Despite being known, they were not adopted in other countries where wages were low and energy expensive.
- Why were they invented in Britain rather than elsewhere in Europe? The bias of the technical change implies that R&D was a profitable investment in Britain but would not have been in other countries.

The invention of coke smelting

Coke smelting is one of the famous inventions of the industrial revolution and had an enormous long run impact, for it was essential for the production of cheap iron, which, in turn, was required for the railroad, metal steam ships, and the general mechanization of industry. The invention of coke smelting clearly illustrates the themes of this essay: It was a little idea, not a big idea. Initially, coke iron was more expensive than charcoal iron, and the first problem was to develop a market for the new product. This was accomplished through an R&D program to make thin-walled castings. The second problem was to cut production costs, so coke iron was competitive with charcoal iron for refining into wrought iron. This problem was solved inadvertently as problems of irregular water supply were addressed. Coke smelting was a biased technical improvement, which was not profitable to use in most of Europe, and would not have been profitable to invent outside of Britain. That is why the discovery was made in Britain rather than France.

How much creativity did coke smelting require? What engineering problems did it pose?

Coke smelting did not depend on any scientific discovery nor did it require an act of genius. In fact, it required almost no thought at all. Coal was a much cheaper source of energy than wood, and attempts were made to substitute the cheaper fuel in most applications during the seventeenth century. If coal was being burnt to heat the house, why not chuck it into the blast furnace instead of expensive charcoal? And, indeed, there are many examples of people doing just that in the seventeenth century. Dud Dudley was an early pioneer who claimed in his book *Metallum Martis* (1665) to have successfully smelted iron with coke, and he had the iron goods around his house to prove it. Others followed, and there is no reason to believe that they failed. The problem was that the process was not economic. Most iron in the seventeenth century was refined into wrought iron, and pig iron smelted with coal contained too much sulfur for this to be successful. This was a typical problem in substituting coal for wood: the coal introduced impurities, so new technology had to be invented to eliminate them. Wrought iron was not successfully made from mineral fuel pig iron until the middle of the eighteenth century.

Abraham Darby I is usually credited with the invention of coke smelting, but, as noted, he did not conceive the idea. Darby probably learned about coke smelting from Shadrach Fox, who had a contract to supply the Board of Ordnance with cast iron shot in the 1690s. This iron was probably smelted with coke, and the Fox's furnace was the one at Coalbrookdale that Darby later leased. The furnace blew up in 1701, and Fox smelted some more iron with coal or coke at the Wombridge Furnace. Darby leased the Coalbrookdale from Fox in 1708, rebuilt it, and set off on his career smelting coke iron (King 2003, p. 52).

The link from Fox to Darby solves several puzzles—why Darby never patented coke smelting (although he patented a casting process) and how he had the confidence to use coke from the very inception of his business. He seems to have known the process would work technically, for he did no experimenting with coke nor does he seem to have had a back-up plan to use charcoal if coke smelting failed. Also, Shadrach Fox's experience showed that coke iron was suitable for castings, which was the application Darby had in mind.

Darby's R&D project

Indeed, Darby's contribution to 'inventing' coke smelting was in finding a commercially viable application for the material. In about 1702, Darby and other Quakers established the Baptist Mills Brass Works near Bristol. Most brass was then fabricated by drawing it into wire or by hammering sheets into pots, kettles, and such like. Casting was traditionally limited to church bells and canon. However, by the late seventeenth century, the Dutch were casting many other products using sand moulds and reusable patterns. In 1703, Darby set up his own foundry and tried to cast iron pots with sand moulds, but he was unsuccessful. In 1704, he went to the Netherlands to study sand casting. He brought back some Dutch workers and got them to try casting iron, but they were also unsuccessful. However, an English apprentice, John Thomas, believed he could do it, and Darby paid him until he was successful in 1707. This was Darby's principal R&D project, and it resulted in a patent for casting iron with sand molds. Darby's partners in Baptist Mills did not want to pay for this research, but he found a new financial backer in Thomas Foudney.

When Darby leased the Coalbrookdale furnace from Shadrach Fox, his plan was to smelt pig iron and cast iron pots with sand moulds. Not only were the castings successful,

but the silicon in the coke iron rendered it more fluid than charcoal iron, so it proved possible to make pots with thinner walls that sold at a higher price. This was essential for the success of coke smelting since the iron itself was expensive. This was the process that Darby patented (Mott 1957-9, p. 78, Hyde 1977, pp. 40-1).

The smelting process involved two further examples of technological borrowing. The first was in the manufacture of coke. Darby had learned how to make coke when he was apprenticed to a maltster, for coke had been invented for that use (Mott 1957, Raistrick 1989, pp. 23, 25). The second was the use of the reverberatory furnace to remelt the pig iron for casting. Reverberatory furnaces had been used since the middle ages to melt the brass for bell founding, and Dud Dudley may have used such a furnace to cast iron. In the 1670s and 1680s, the reverberatory furnace was used to smelt lead and copper by two chartered companies associated with Sir Clement Clark, who may have experimented with melting iron. Darby was the first to make a commercial success of the reverberatory furnace in the iron foundry (Mott 1957-9, p. 76, King 2003, p. 51). Evidently, Darby's plan to cast pots with coke pig iron did not come out of nowhere. It was the combination of several recent developments in the iron and copper industries.

For the first half of the eighteenth century, coke smelting was limited to only a few furnaces making foundry pig, for the metal was too expensive and impure to refine into wrought iron, the main product of the industry. This problem was overcome through 'learning by doing' or, more exactly, through inadvertent discovery made in the course of solving other problems. The bellows of blast furnaces were run with water power, and a dry summer meant that the water level dropped in the reservoir supplying the wheel resulting in a fall off in blast and reduced iron production. This problem was resolved at Coalbrookdale by installing a Newcomen steam engine to recycle water by pumping it from the outflow of the water wheel back into the supply reservoir. Coalbrookdale was one of the first firms to use this process (Raistrick 1989, pp. 107-115). As was the case with Warmley, coal was mined at Coalbrookdale, and the cheap fuel made the Newcomen engine feasible.

The improved water supply resulted in stronger, more regular blast to the furnace, and that had the unintended consequence of cutting fuel consumption. Lower fuel consumption, which was an *energy-saving* technological improvement, cut costs enough to make coke iron competitive with charcoal. Coke iron production took-off after mid century.

Coke smelting was a biased technical improvement that reduced costs in Britain more than on the continent.

By replacing charcoal with coke, Darby's smelting process cut costs in localities where coal was cheap. Since most coal in Europe in the eighteenth century was mined in Britain, coke technology (once perfected) conferred a great advantage on Britain. Conversely, coke smelting was pointless where coal was as dear as it was in most Europe before the mid-nineteenth century. As late as the 1840s, 80% of French and Prussian iron was charcoal. Belgium is the exception that proves the rule, for it shifted early to coke, and it was also the only part of the continent with large scale coal mining in the eighteenth century and a price structure like Britain's (Landes 1969, p. 217). While Landes has argued that Britain's lead is evidence of superior entrepreneurship, Fremdling (2000) has shown that coke iron did not pay on the continent before the 1850s. Production costs explain the diffusion of the technology—not attitudes to innovation.

Why not France?

It took almost a century from the perfection of coke smelting at Coalbrookdale until its use was widespread on the continent. During that period, the technology was well known and freely available but not adopted. Since it conferred no benefit to French or German producers, there would have been no point in developing it in those countries. It was not the impracticality of the engineering culture that explains the lack of attention to coke smelting. Inventing the process would not have paid.

The invention of cotton spinning machinery

How much creativity did mechanical spinning require? What engineering problems did it pose?

The spinning jenny and water frame were not based on scientific discoveries. Were they instead ‘macro inventions’ that required enormous leaps of the technological imagination? To know, we must see if the spinning machines really did spring *ab nihilo* or whether they had genealogies that indicate less dramatic departures from previous practice. I begin with hand spinning to highlight the technical problems that Hargreaves and Arkwright faced.

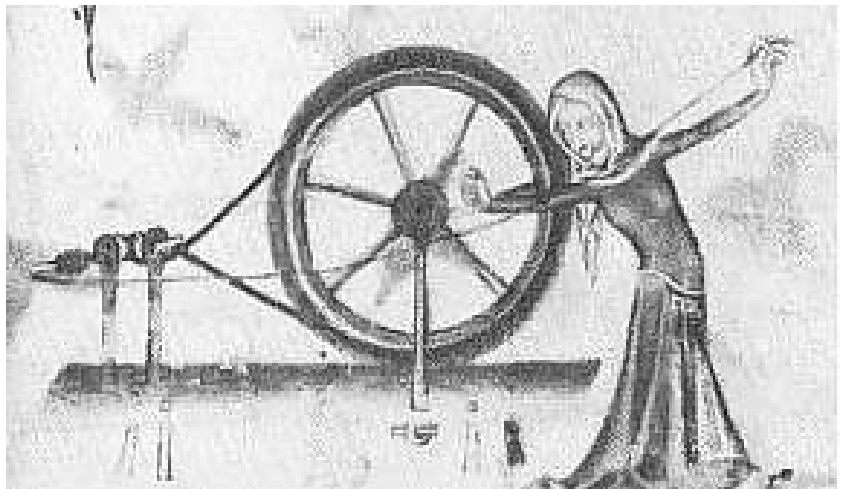
Figure 7 shows a spinning wheel in operation. The raw cotton was first carded to produce a roving, which was a loose

length of cotton fibres. The two key operations in spinning were drawing out the roving so it became thinner and then twisting it to impart strength. In the late medieval period, this was done with a ‘spinning wheel’. It consisted of three parts—the wheel itself, the spindle, and the string that acted as a belt to connect the wheel to the spindle. Sometimes a treadle was connected to the wheel so that the spinster could turn it with her foot; otherwise she used her right hand. She held the roving in her left hand, and its other end was attached to the

horizontal spindle. The wheel was spun, and the spindle rotated. The spinster pulled back the roving so that it thinned out and then moved her hand to the left. This allowed the thread to slip off the end of the spindle each time it rotated. Each time that happened, the thread was twisted once. When enough twist was imparted, the spinster moved her left hand to the right, so it was once again between her and the spindle. In this position, the thread was wound onto the spindle. The process was repeated as the next few inches of roving were pulled away from the spindle to be thin out in turn.

It is hard to see anything that came *ab nihilo* in Hargreaves’ spinning jenny. It was little more than a spinning wheel on its side with several spindles connected by belts to a common wheel. Indeed, the story is that Hargreaves conceived the jenny when he saw a spinning wheel fall over and continue spinning while it was on the ground. A sliding frame replaced the spinster’s left hand and drew the rovings away from the spindles. The difficulty, as with most eighteenth century technology, lay in working out of the details of the linkages

Figure 7



and rods that drew out the cotton roving. The spinning jenny was an engineering challenge. It did not require a scientific breakthrough or a great leap of imagination.

Arkwright's water frame was another spinning technique that was more portentous in its consequences and arguably more clever in its design. But, again, it was based neither on a scientific breakthrough nor on an original idea.

Figure 8 shows a water frame, and Figure 9 is a close-up of the 'clockwork'. The rovings entered at the top. They then passed through three pairs of rollers. The rollers operated like mangels, pulling the cotton between them. The second pair spun at twice the speed of the first, and the third doubled the speed again. For

this reason, the first pair of rollers simultaneously pulled the roving into the mechanism and at the same time held it back with respect to the second pair, which was spinning faster and tugging it forward. The cotton was, thus, stretched and thinned out as it went between the two pairs of rollers. The stretching was repeated between the second and third pairs of rollers since the third pair spun faster than the second. In this way, the water frame accomplished the first task in spinning—drawing out the fibre.

The second task was accomplished by the flyers, which spun around at the bottom of the frame, simultaneously twisting the fibre and coiling it on the bobbin.

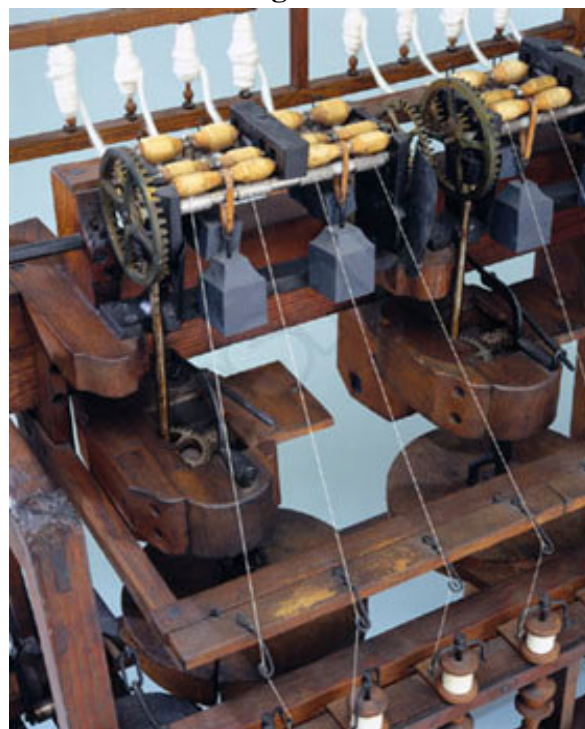
Not much of this was original with Arkwright. The flyer, indeed, was an old device and none of the cotton inventors could take credit for it (another example of copying). The novelty of the water frame lay in the trains of rollers that drew out the cotton. This idea, however, was not Arkwright's either: Wyatt and Paul took out patents on the idea in 1738 and 1758. Much effort was put into perfecting the machine, licenses were sold, and they erected their own factory in Birmingham. It was not successful, although Matthew Boulton thought it might have been had it been well managed. The Wyatt and Paul R&D program was a failure.

If there were any macro inventors, they were Wyatt and Paul. But were they? The test of a macro-invention is whether it was conceived ab nihilo or whether it had a pedigree that shows that it involved only a small variation in practice. By that test, roller spinning was a micro-invention. Rollers were a general purpose

Figure 8

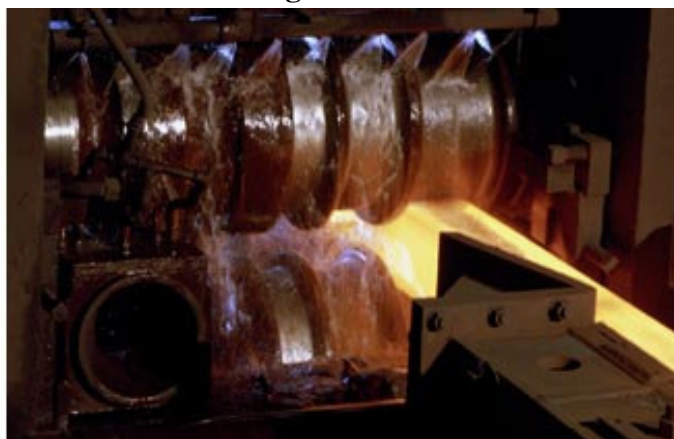


Figure 9



technology whose use was spreading in the early eighteenth century.⁸ Rollers had a long history in metallurgy where bars, ingots, plates, and nails were shaped (Figure 10). Coin faces were pressed into gold and silver with engraved rollers. Indeed, the similarities between a metal rolling mill and roller spinning were so great that Rees (1819-20, II, p. 173) reports that Arkwright conceived of roller spinning when looking at a rolling mill. There are sixteenth and seventeenth century designs for corn mills using rollers. In the late seventeenth century, cast glass was rolled at Saint-Gobain and polished with a roller. Cloth was pressed by rollers under enormous weight in the calendering process. In 1696, the Paris mint was using rollers. In the late seventeenth century, ‘milled’ sheet formed by rolling lead replaced cast lead sheet. In 1670, the Dutch developed a roller device with spikes to tear up rags for paper making and in 1720 applied rollers to pressing paper. Rollers were also used to crush rock. Applying rollers to stretching cotton was no doubt clever, but the idea had a history. When he discussed Cort’s invention of puddling and rolling, Mokyr (1993, p. 22) discounted it as a macro invention since rolling had a long history in metallurgy. The same argument applies to cotton. Rollers were in the air in the first half of the eighteenth century. Wyatt and Paul did not think them up from nowhere. Roller spinning was not a macro invention.

Figure 10



Hargreaves’ and Arkwright’s R&D projects

The challenge with roller spinning was making the idea work. Hargreaves faced the easier challenge. His first jenny was reportedly made with a pocket knife, but getting a design that could be operated satisfactorily took from 1764 to 1767 (Aspin and Chapman 1964, p. 13). Hargreaves began trying to realize money from his invention almost immediately by selling jennies. He moved to Nottingham. As he continued to improve the jenny he needed a financial backer. He first went into partnership with a man named Shipley and later with Thomas James (Aspin and Chapman 1964, 19, 22-3, 34-5). They established a spinning factory. In 1770, Hargreaves patented the jenny, but it was too late. His patent was challenged in court and eventually voided on the grounds that he had sold jennies before it was issued. Despite the widespread use of the jenny in the late eighteenth century, Hargreaves realized very little money from the invention.

Arkwright’s challenge was far greater. Figure 11 shows Wyatt and Paul’s diagram from their second patent, and it can be compared to the Arkwright machine to see the engineering problems involved. Both devices used a flyer to twist and wind the finished thread. Wyatt and Paul’s diagram shows one pair of rollers, whereas Arkwright’s frame had

⁸Singer, et al. (1957, Vol. III, pp. 16-7, 32, 45, 47, 177, 238-9, 340-4, 414-5), Raistrick 1972, p. 91), Rowe (1983, pp. 8-10), Beveridge (1939, pp. 191-2, 287-9, 485-9, 652-6) Mokyr (1990, p. 60), Hunter (1930, pp. 170-1).

three. It was essential to have several in a series so that they could pull against each other. Wyatt and Paul did mention two pairs in the description of the machine in their first patent: Deciding the number of rollers was a development challenge, and it looks as though Wyatt and Paul went down a wrong alley in their R&D program by trying to develop a machine with only one set of rollers.

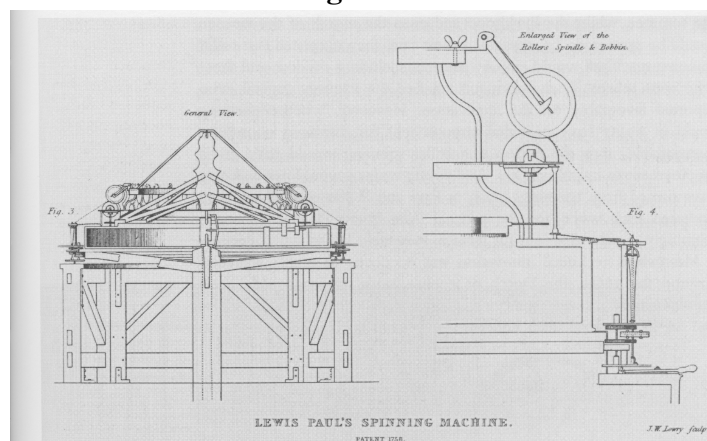
They never confronted, therefore, the other development challenges that Arkwright overcame in the 1760s. These included:

- The increase in speed from one set of rollers to the next. In the early water frame displayed in Strutt's North Mill, Belper rotation speed doubles from one train of rolls to the next.
- How to arrange the gears to connect the main power shaft to the rollers and coordinate their movements. The rollers and gears were produced as a module known as the 'clock work' in recognition of the apparatus that inspired it.
- The spacing between the rollers. The distance had to be slightly less than the length of a cotton fibre. That allowed stretching and thinning of the thread since a fibre that was past the grip of the first rollers and caught by the second pair could be pulled ahead of an adjacent fibre that was held by the first rollers but not yet in the grasp of the second. If the rollers were too close, all of the fibres would be gripped by both pairs, so there would be no stretching. If the rollers were too distant, the thread would be pulled apart: Proper operation required some fibres to be gripped by both rollers to prevent breakage, while others were held by one or the other pair for thinning. Thought and experimentation were required to work this out.
- The materials with which to make the rollers. One was grooved metal and the other wood covered with leather. They had to pull the fibre without catching.
- The pressure with which the top roller pressed down on the bottom one. This was regulated by hanging weights from the top ones, as shown in Figure 9. The optimal weight could only be determined by repeated trials.

The point of this discussion is to emphasize the real issues involved in 'inventing' mechanical spinning. The originality was not in thinking up the roller; rather, the challenges were the practical issues of making the roller work in the application. Wyatt and Paul spent some years on this, but did not succeed. Arkwright employed clockmakers over a five year period to perfect the design. We have no record of exactly what they did, but the comparison of the Wyatt and Paul design with Arkwright's frame highlights the problems they faced. These challenges could only be met by constructing models or experimental prototypes. 'Inventing' the water frame involved a significant R&D program.

The R&D program had very modern financial implications that are worth noting. First, the object was to make money for Arkwright, and patenting the invention was the essential step in securing that income. This was done in 1769. Second, there was the formidable problem of financing the R&D. Arkwright did what modern inventors do: he found venture capitalists—'projectors' in the language of the eighteenth century. His patent was jointly held with John Smalley and David Thornley, and each partner was committed to

Figure 11



finance one third of the development costs. Quickly they ran out of money, and Samuel Need and Jedediah Strutt were brought in as partners. Strutt was an established ‘projector,’ who had already made a fortune financing improvements in frame knitting. Development work continued. Strutt himself suggested dusting the rollers with chalk to prevent the cotton from sticking to them. Several cam operated devices were added to wind the thread, raise and lower the bobbins and move the thread back and forth along the rollers to prevent a groove’s being worn in the surface. In 1774, Jedediah Strutt claimed that £13,000 had been spent on developing Arkwright’s device. This included the construction of buildings, which posed problems of layout and power transmission, and it indicates the scale of the finance required to turn the idea of roller spinning into the reality of a working cotton mill (Hills 1970, pp. 60-71).

Roller spinning was not unusual. If we examine the revolutionary inventions of the eighteenth century, we see that they were not based on revolutionary ideas. They were based on little ideas and often on copying products and practices from other places or industries. Success depended on solving the engineering problems in making the simple idea work. Edison famously remarked that ‘invention was 1% inspiration and 99% perspiration.’ Sweat was at least as important in the eighteenth century as it was in the late nineteenth. Mokyr (1993, p. 33) correctly observed that Britain ‘had a *comparative* advantage in *microinventions*.’ The questions are where that advantage came from, and why it was activated.

What was the motive for mechanizing spinning?

Mechanical spinning was a child of globalization. India was the world’s greatest cotton textile producer, and the East India company imported vast amounts of printed cotton cloth. This was important for later developments, for it showed that there was a large British market. So much was imported, that wool and linen manufacturers succeeded in 1701 in having printed cotton fabrics excluded from Britain. The import of white cottons was still permitted, and printing was done in England. A small British production of cotton cloth ensued. In 1721, the ban was extended to all cotton fabrics: the domestic production and consumption of purely cotton fabrics was made illegal. “The Lancashire cotton industry...secured in 1736 a relaxation for goods of flax warp and cotton weft [called fustians], a relaxation which by custom (or subterfuge) came to cover the great bulk of the industry’s production and even, it is probable, the growing part of it that used hand-spun cotton twist for warps,” i.e. all cotton cloth (Fitton and Wadsworth 1958, p. 68). English cotton producers, thus, received ambiguous protection from Indian imports. Similar restrictions were imposed in other European countries. While offering domestic protection, the laws did permit the importation of Indian cottons for re-export, and that market boomed with the growth of the slave trade in the mid-eighteenth century, for cotton cloth was bartered with African chiefs for slaves. This was another market which British producers could hope to supply—if their costs were competitive.

Britain’s high wage economy affected the cotton industry in two respects. First, the high incomes of British workers underpinned the mass market in cloth that was revealed during the period of unrestricted imports (Lemire 1991, p. 55). Second, at the exchange rate, British wages were considerably higher than Indian wages. While distance provided some protection, English spinners could only compete in producing the coarsest yarn, which was the least labour intensive.

Lowering labour costs was the key to competitiveness. There was a large potential

domestic market, and a vast foreign market supplied by India and other producers. Cost reductions promised a large increase in market share and immense fortunes for the successful innovators—both of which were realized through mechanization.

Why not France?

Globalization affected other European countries as it affected England. For much of the pre-industrial period, France had possessions in India and was flooded with Indian calicoes in the late seventeenth century. Their importation was banned in 1686. France also had new world colonies and was active in the slave trade where French ships carried about 40% of the volume of English ships (Curtin 1966, pp. 211-2). French producers had an African market, albeit a smaller one than the English. In 1786, when English production was already soaring as mechanized spinning spread, Britain imported 18 million pounds of raw cotton, while France imported 11 million (Crouzet 1985, p. 32). The French cotton market was substantial, and French manufacturers had opportunities to compete against Indian textiles in Africa like their British counterparts, a feature emphasized by Inikori (2002, pp. 427-51).

And yet the French not only failed to invent mechanized spinning, they did not adopt it even when it was freely available. This was not for lack of knowledge. John Holker was an English Jacobite, who fled to France in 1750 where he established himself as a cotton manufacturer. In 1754, he succeeded in being appointed Inspector General of Foreign Manufactures charged with importing successful foreign technology. In 1771 he sent his son to Lancashire to report on the new machines, and his son brought back a jenny. This was copied and made available to French producers; indeed, the state subsidized its use. It was installed in some large scale factories but was otherwise ignored by the cotton trade. In 1790, there were about 900 jennies in France compared to 20,000 in England (Aspin and Chapman 1964, p. 49). The disproportion was at least as great with water frames. About 150 large scale mills were in operation in Britain in the late 1780s. In France, there were only four and several of these were extremely small and not representative of British practice. (Wadsworth and Mann 1931, pp. 193-208, 503-6, Chapman and Butt 1988, pp. 106-11).

Why did the French ignore the new spinning machines? Cost calculations for France are not robust, but the available figures indicate that jennies achieved consistent savings only at high count work, which was not the typical application (Ballot 1923, pp. 48-9). In France, a 60 spindle jenny cost 280 livre tournois in 1790 (Chassagne 1991, p. 191), while a labourer in the provinces earned about three quarters of a livre tournois per day, so the jenny cost 373 days labour. In England, a jenny cost 140 shillings and a labourer earned about one shilling per day, so the jenny was worth 140 days labour (Chapman and Butt 1988, p. 107). In France, the value of the labour saved with the jenny was not worth the extra capital cost, while in England it was. French cost comparisons show that Arkwright's water frame, a much more capital intensive technique, was no more economical than the jenny. The reverse was true in England where water frames were rapidly overtaking jennies. The French lag in mechanization was the result of the low French wage.

Global competition was the impetus to invent mechanical spinning. The result was a biased technical improvement that benefited Britain with its high wage economy much more than continental producers like France.

Why the British rather than the French invented mechanical spinning

As we have indicated, both the jenny and the water frame required considerable expenditures in R&D to make them work. The same would have been true in France. Would these expenditures have been worthwhile in France? No—mechanized spinning brought no economic benefit there in view of the low wage. We need look no further to understand why the spinning jenny and the water frame were invented in England rather than France or, indeed, most other parts of the world.

Steam engine

An idea from science

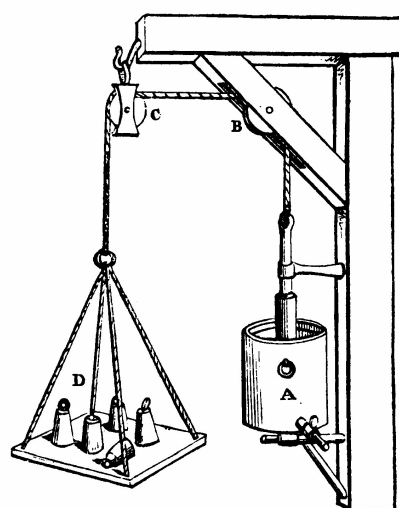
The steam engine presents a variation on the theme. Big Ideas did not have much to do with coke smelting or mechanized spinning, but the low pressure steam engine, developed by Newcomen and improved by Watt, was the best example of a scientific spin-off in the eighteenth century. It was based on the idea that the atmosphere had weight, which was a seventeenth century discovery and a hot topic in experimental physics. Even in this case, however, economic incentives were a key to the application of this new knowledge. Without the British coal industry, the steam engine would not have been developed.

The link from science to the steam engine was direct. The science began with Galileo, who discovered that a suction pump could not raise water more than about 34 feet—despite a vacuum existing above the column of water that had been drawn up to that height. Aristotle had said that nature abhorred a vacuum but only, it seemed, for 34 feet! Galileo suggested to Evangelista Torricelli, his secretary, that he investigate this problem. In 1644 Torricelli inverted a glass tube full of mercury and placed its bottom in a bowl of mercury. The mercury stabilized in the tube forming a column 76 centimeters high with a vacuum above it. This was the world's first barometer, and Toricelli concluded that the atmosphere had weight and pushed the mercury up the column. This was confirmed in 1648 by placing the barometer in a larger container and pumping the air out of it—the column of mercury collapsed and then reappeared as air was readmitted into the larger container.

A particularly important set of experiments was performed in Magdeburg by Otto von Guericke. In 1655, he put two hemispheres together and pumped the air out of the space they enclosed. It took sixteen horses to pull them apart. In another portentous experiment in 1672, von Guericke found that if the air was pumped out of cylinder A (Figure 12), the weights D rose as the atmosphere pushed the piston down into the cylinder. Evidently, the weight of the air could perform work.

This idea had been anticipated by Christian Huygens in 1666 who used exploding gun powder to drive a piston up a cylinder. When it reached the top, the gases from the explosion were released creating a vacuum. Air pushed the piston down and raised the load. This design was not effective. However, his assistant, Denis Papin, realized that filling the cylinder with steam and then condensing it accomplished the same purpose. In 1675, Papin built the first, very crude steam engine.

Figure 12



The first practical application of steam technology was Savery's steam vacuum pump patented in 1698. It created a vacuum by condensing steam in a reservoir; the vacuum then sucked up water. The purpose of Savery's device was draining mines, but it was not widely used, and it was not a steam engine.

But still an R&D project

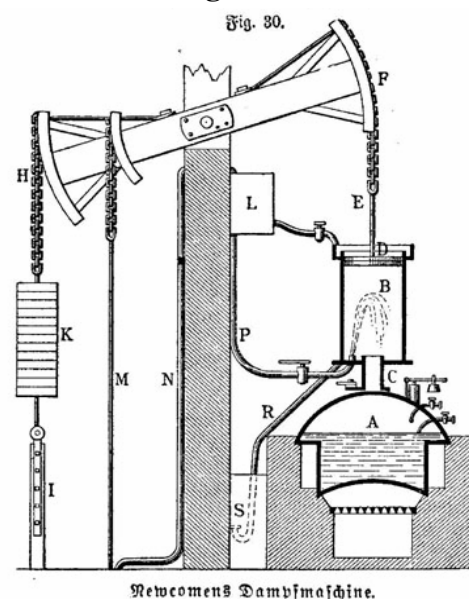
The first successful steam engine was invented by Thomas Newcomen.⁹ Like Savery's device, it was intended to drain mines. Newcomen's engine applied the discovery that the atmosphere has weight. That application required a major R&D project, and that project meant that the invention was an economic commitment as well as a scientific spin-off.

Newcomen's design (Figure 13) was suggested by von Gierecke's apparatus: First, replace the weights with a pump (I). Second, construct the 'balance beam' so it is slightly out of balance and rests naturally with the pump-side down (H). Then, if a way were contrived to create a vacuum in the cylinder (B), air pressure would depress the piston (E) and raise the pump. Next, if air were reintroduced into the cylinder, the vacuum would be eliminated and the pump would drop since the beam is slightly out of balance. Finally, recreating the vacuum would raise the pump again since the pressure of the atmosphere would again depress the piston. Thus, creating a vacuum and relieving it raises and lowers the pump. This apparatus becomes a 'steam engine' when steam is made by boiling water (A) and drawing it into the cylinder when the piston is raised, and the vacuum is created when cold water is injected into the cylinder (B) to condense the steam. This is a low pressure engine since it is not steam pressure that pushes the piston up: the point of the steam is simply to provide a gas that fills the cylinder and which is condensed to create the vacuum. At the heart of the Newcomen engine was seventeenth century science.

While the Newcomen engine differed from other eighteenth century inventions in its scientific basis, it was similar in the engineering challenges it posed. Twentieth century engineers who have built Newcomen engines have found it to be tricky and difficult to make them actually work (Hills 1989, pp. 20-30). That Newcomen could resolve the engineering problems was a remarkable achievement. He began experimenting around 1700 and apparently built an engine in Cornwall in 1710, two years before his famous engine at Dudley.

In this decade of R&D, Newcomen learned many things. He discovered by accident that the steam could be condensed rapidly if cold water was injected into the cylinder (B). He found that the water supply tank (L) for the injector worked best if it was placed at the top of the engine house, so the injection water entered the cylinder at high pressure and volume. The pipe (R) that drained the condensed water from the cylinder had to run far enough down into a hot well (S), so that atmospheric pressure could not force condensed water back into

Figure 13



⁹Recent work on the development of the steam engine includes Hills (1989), Nuvolari (2004a), von Tunzelman (1978).

the engine. The top of the cylinder had to be sealed with a layer of water—nothing else worked. The dimensions of the balance and the weights of the engine's piston and the pump (K) had to be coordinated for smooth operation. Linkages between the beam and the valves had to be designed so that they would open and shut automatically at the correct moments in the cycle. No wonder it took Newcomen ten years to create an operating engine. It was a time consuming and expensive undertaking.

Like many practitioners of R&D, Newcomen hoped for a pay-off through patenting his creation. In this he was frustrated because the Savery patent was extended 21 years to 1733 and construed to cover his very different engine! Newcomen was forced to do a deal with the Savery patentees to realize any income at all.

A biased technical improvement that favoured the British

R&D costs mean that the link between Galileo and Newcomen was mediated by economics. Scientific curiosity and court patronage may have been reason enough for Torricelli, Boyle, Huygens and other scientists to devote their time and money to studying air pressure (David 1998), but Newcomen was motivated by prospective commercial gain. What was that gain? The object of the engine was to drain mines, so the demand for the technology was determined by the size of the mining industry. In 1700, England's lead was immense: It produced 81% of the tonnage in Europe and 58% of the value. Germany, which had been Europe's mining centre in the late middle ages, produced only 4% of the tonnage and 9% of the value in 1700. The change was all down to coal. Servicing the drainage needs of England's coal industry is one reason why steam engine research was carried out in England.

Coal mattered for a second reason as well. There were alternative ways of powering pumps—water wheels or horse gigs—so there was effective demand for steam power only if it was cost-effective. The early steam engines were profligate in their consumption of fuel, so they were cheap sources of power only if fuel was remarkably cheap. Desaguliers (1744, II, pp. 464-5), an early enthusiast of steam power, put the matter succinctly:

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

The Newcomen engine was a biased technological improvement that shifted input demand away from animal feed and towards combustible fuel.

Free fuel overcame high fuel consumption, but, by the same token, the energy-intensity of the Newcomen engine restricted its use to the coal fuels. Since most of the coal mines were in Britain, so were most of the engines. At the expiry of the Savery-Newcomen patent in 1733, there were about 100 atmospheric engines in operation in England. By 1800, the total had grown to 2500 in Britain of which 60 - 70% were Newcomen engines.¹⁰ In

¹⁰Kanefsky and Robey (1980, p. 171). The uncertainty depends on how one classifies the engines of unknown type. As the production of Watt engines is reasonably well established, the unknown engines were probably Newcomen, and that choice yields the higher

contrast, Belgium, with the largest coal mining industry on the continent, was second with perhaps 100 engines in 1800.¹¹ France followed with about 70 engines of which 45 were probably Newcomen (installed mainly at coal mines) and 25 were Watt. The first steam engine was installed in the Netherlands in 1774, in Russia in 1775-7, and in Germany at about the same time. None seem to have been installed in Portugal or Italy (Redlich 1944, p. 122, Tann 1978-9, p. 548, 558). The Newcomen engine “was adopted in numbers only in the coal fields...The machines were, until well into the 19th century, so symbolically linked to the coal-fuel matrix in which they had come to maturity that they could not readily pass beyond its limits” (Hollister-Short 1976-7, p. 22). The diffusion pattern of the Newcomen engine was determined by the location of coal mines, and Britain’s lead reflected the size of her coal industry—not superior rationality.

Why the steam engine was invented in Britain rather than France or China

Moreover, the diffusion pattern of the Newcomen engine indicates that it would not have been invented outside of Britain during the eighteenth century. Non-adoption was not due to ignorance: The Newcomen engine was well known as the wonder technology of its day. It was not difficult to acquire components, nor was it difficult to lure English mechanics abroad to install them (Hollister-Short 1976). Despite that, it was little used. A small market for engines implied little potential income for a developer to set against the R&D costs. The benefit-cost ratio was much higher for Newcomen than for any would-be emulator on the continent. Newcomen had to know about the weight of the atmosphere in order to make his engine work, but he also needed a market for the invention in order to make its development a paying proposition. The condition was realized only in Britain, and that is why the steam engine was developed there rather than in France, Germany, or even Belgium.

Why did the industrial revolution lead to modern economic growth?

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 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. Wouldn’t the French, or the Germans, or the Italians, have produced an industrial revolution by another route? Weren’t there alternative paths to the twentieth century?

These questions are closely related to another important question asked by Mokyr: Why didn’t the industrial revolution 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

percentage.

¹¹The total is very poorly established and is surmised from an estimate of 200 engines installed in France (then including Belgium) in 1810 made by Perrier, the first important French steam engine manufacturer (Harris 1978-9, p. 178).

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 (1962), 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. 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 were the immediate explanations of the continuation of economic growth until the First World War. Those developments were: (1) the general mechanization of industry, (2) the railroad, (3) steam powered, iron ships (Crafts 2004). 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 (O'Rourke and Williamson 1999).

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 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 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. The main producers were in Asia. As a result, the price elasticity of demand for English cotton was extremely large. If Britain could become competitive, it could expand production enormously by replacing Indian and Chinese producers. Mechanization led to that outcome. 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. But 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 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 (von Tunzelman 1978, pp. 175-225). 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, knitting—did not lead to general mechanization or globalization. One of the social benefits of an invention 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 went through northern Britain.

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