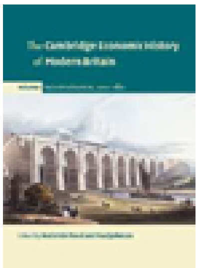

The Cambridge Economic History of Modern Britain

Edited by Roderick Floud, Paul Johnson

Book DOI: http://dx.doi.org/10.1017/CHOL9780521820363

Online ISBN: 9781139053853

Hardback ISBN: 9780521820363

Paperback ISBN: 9780521527361

Chapter

Chapter1 - Accounting for the Industrial Revolution pp. 1-27

Chapter DOI: http://dx.doi.org/10.1017/CHOL9780521820363.002

Cambridge University Press

1 Accounting for the Industrial Revolution

JOEL MOKYR

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INTRODUCTION

How do we account for the Industrial Revolution?[1] In recent years, economic historians have had to redefine what they mean by the industrial revolution and to reassess its significance. On the one hand, the findings published in the 1990s by Crafts, Harley (Crafts and Harley 1992; Harley 1998) and others have reduced estimates of the rate of economic growth during the classic years of the industrial revolution, 1760 to 1830. These findings have been reinforced by recent work by scholars such as Antràs and Voth (2003) and Clark (2001b), who have shown that the sharp revisions downward to Deane and Cole's (1967) estimates of the rates of growth and productivity change during the industrial revolution made by Crafts and Harley were, if anything, too optimistic and that little if any real per capita growth can be discerned in Britain before 1830. These conclusions are consistent with Feinstein's (1998) recalculations of the growth in real wages, which showed very little secular increase before the mid-1840s. As a macroeconomic phenomenon, then, the Industrial Revolution in its 'classical years', 1760–1830, stands today diminished and

[1] I am grateful to Gregory Clark and Joachim Voth for making unpublished papers easily accessible and to E. A. Wrigley, Knick Harley and Maxine Berg for insightful comments. Some of the materials in this chapter are adapted from my editor's Introduction, 'The new economic history and the industrial revolution', in Mokyr (1999); from my chapter 'Knowledge, technology, and economic growth during the industrial revolution', in Van Ark *et al.* (2000); and from Mokyr (2002).

weakened. It is now also widely realised that the Industrial Revolution was not 'industrialisation'. On the eve of the Industrial Revolution Britain was a highly developed, commercialised, sophisticated economy in which a large proportion of the labour force was engaged in non-agricultural activities, and in which the quality of life as measured by the consumption of non-essentials and life expectancy was as high as could be expected anywhere on this planet. In many ways, life did not improve all that much between 1750 and 1850. So perhaps the concept of an industrial revolution is indeed the product of an obsolete historiography.

It is possible to exaggerate this view. We need to recall first that the Industrial Revolution took place in a period of almost incessant war, and that wars in these years – as Ricardo pointed out in an almost forgotten chapter in his *Principles* (1951 [1817]) – meant serious disruptions in the patterns of trade and hence income loss through foregone gains from trade. The peace of Paris (1763) was soon followed by the American Independence Wars, the Revolutionary Wars, Napoleon, Jefferson's embargo and the war of 1812–14. These were compounded by harvest failures, the worst of which (1816) occurred right after the wars ended. Finally, between 1760 and 1830 the population of England rose from 6.1 million to 13.1 million, an increase that had no precedent in the country's history or equal in the European experience outside the British Isles in this period. One does not have to be a committed Malthusian to accept that for most 'pre-industrial' economies such a sudden demographic increase would have created serious stresses and resource scarcities. The very fact that despite these pressures Britain was able not only to maintain living standards and prevent truly damaging scarcity, but also to finance a set of expensive wars on the continent, demonstrated that by 1780 or 1790 her economy had reached a resilience and strength that exceeded by a large factor that found by William III upon arrival in Britain in 1688. Indeed, had the years of the Industrial Revolution coincided with peace and more abundant harvests, or had population growth been less fast, real wages and income per capita would have in all likelihood increased faster.

Moreover, the striking historiographical phenomenon is that the importance of the Industrial Revolution as a historical dividing line has recently been underlined by scholars writing in the traditions of 'world history' because of the growing realisation that until late in the eighteenth century the economic gap between Europe and the Orient was less than earlier work had suggested. As early as 1988, Eric Jones suggested in his *Growth Recurring* that episodes of growth took place in Asia as much as in Europe, and that before the industrial revolution it would have been hard to predict that the one episode that would 'break through' and create *sustained* growth would happen in Europe and specifically in Britain. This work has suggested that the differences in the early modern age between Europe and parts of the Orient have been overdrawn and that as late as 1750 the gap between West and East was comparatively minor: a number of scholars have argued that economic performance and living standards in western Europe did not really diverge from those in the Orient (specifically the Yangzi delta in China and Japan) until the nineteenth century (Hanley 1997; Pomeranz 2000; Vries 2001a, 2001b; Goldstone 2002). Given the huge gap between the West and the rest in 1900, the realisation that the gap may not have been all that large in 1750 places an additional onus of responsibility for historical change on the period after the mid-eighteenth century.

It is ahistorical to think about industrial revolutions as events that abruptly raise the rate of sustained economic growth by a considerable amount. Most of the effects of invention and diffusion on income per capita or economic welfare are slow in coming and spread out over long periods. All the same, we should recognise that even though the dynamic relation between technological progress and per capita growth is hard to pin down and measure, it is the central feature of modern economic history. We do not know for sure how to identify the technology-driven component of growth, but we can be reasonably sure that the unprecedented (and to a large extent undermeasured) growth in income in the twentieth century would not have taken place without prior technological changes. It seems therefore more useful to measure 'industrial revolutions' in terms of the technological *capabilities* of a society based on the knowledge it possesses and the institutional rules by which its economy operates. These technological capabilities include the potential to produce more goods and services which enter GDP and productivity calculations, but they could equally affect aspects that are poorly measured by our standard measures of economic performance, such as the ability to prevent disease, to educate the young, to preserve and repair the environment, to move and process information, to co-ordinate production in large units, and so on.

These historiographical developments underlie what we may call the paradox of the Industrial Revolution, which I will attempt to account for in this chapter. With the lowering of the estimates of economic growth, some scholars have attempted to suppress the entire notion of the British industrial revolution (J. Clark 1986; Wallerstein 1989; Cameron 1990, 1994; G. Clark 2001b). This attempt has failed, because the notion that contemporaneous economic growth – as traditionally measured using standard national income accounting procedures – was the essence of the 'classical' Industrial Revolution was never established as an axiom. Changes in the British economy and in the larger social and intellectual environment in which production technology operated occurring before and during the classical years of the Industrial Revolution were critical. In the end, this is what accounted for the period of indisputable economic expansion that we observe in Britain after 1830 and the rest of Europe after 1850 and that created the vast gap between Europe and the rest of the world that had emerged by 1914 and still seems to dominate the literature on 'divergence'.

Table 1.1 Estimated annual rates of growth of real output, 1700–1871 (in percentages)

Period	National income per cap. (Deane and Cole)	National income per cap. (Crafts)	Indust. product (Hoffmann)	Indust. product (Deane and Cole)	Indust. product (Harley)	Indust. product (Crafts)	Indust. product (Cuenca)
1700–60	0.44	0.3	0.67	0.74	n.a.	0.62	–
1760–1800	0.52	0.17	2.45	1.24	1.6[a]	1.96	2.61[c]
1800–30	1.61	0.52	2.70	4.4	3.2[b]	3.0	3.18
1830–70	1.98	1.98	3.1	2.9	n.a.	n.a.	–

[a] 1770–1815
[b] 1815–41
[c] 1770–1801

Sources: Computed from Harley 1998; Hoffmann 1965; Cuenca 1994.

ACCOUNTING AND 'ACCOUNTING' FOR THE INDUSTRIAL REVOLUTION

The national income accounting concept of GDP or GNP growth has become associated with economic change for good reason. In principle, it measures what happens to the economy as a whole, not to selected industries or sectors that seem to be unusually dynamic and that may bias the picture. It is the very embodiment of the admonition made by Sir John Clapham, one of the great figures of British economic history of the twentieth century, that any proof by example should face the quantifier's challenge: How large? How long? How often? How representative? It seems all too easy to focus on the dramatic and well-documented inventions in cotton, steam, iron and engineering, and forget the handicraft, construction, food processing, farming and services sectors, which employed the majority of Britons in 1760 in which changes were far slower or non-existent.

Any kind of macroeconomic analysis of the British economy in this period is, as already noted, severely limited by the unavailability of data. Most of what economic historians know about the British economy at the aggregative level has been pieced together from little fragments of data usually collected for a totally different purpose, and held together by a healthy dose of economic analysis. Although the issue still remains a matter of some dispute, it seems that today's consensus is that, at a high level of aggregation, the British economy experienced little growth during the years typically associated with the Industrial Revolution. Most of the computations come from the output side of the national income accounts, and are summarised in Table 1.1.

Compared to Deane and Cole's national income statistics, Crafts' figures reveal an aggregate growth that was much slower during the Industrial Revolution. Industrial production is more ambiguous: Hoffmann's data, computed in the 1930s, clearly show a rapid acceleration during the period of the Industrial Revolution, but Deane and Cole's series is much more erratic and, like the revisionist data of Harley and Crafts, shows that most of the quantitative expansion occurred after 1800.[2] The point to be stressed is that in an economy that is undergoing rapid change in one sector but not in another, aggregate change depends on the relative size of each sector at the *initial moment* and on the interaction between the two sectors. Part of the economic logic of the Crafts–Harley view of slow growth was that productivity growth and technological progress were confined to a few relatively small sectors such as cotton, wool, iron and machinery whereas much of the rest of manufacturing remained more or less stagnant till after 1830. Two-sector growth models imply that abrupt changes in the economy *as a whole* are a mathematical impossibility when the more dynamic sector is initially small, because the aggregate rate of growth of any composite is a weighted average of the growth rates of its components, the weights being the respective shares in output.[3] The British economy as a whole was changing much more slowly than its most dynamic parts such as cotton and machine tools, because growth was 'diluted' by slow-growing sectors (Pollard 1981: 39). It is hardly surprising that it took until 1830 or 1840 for the economy-wide effects of the industrial revolution to be felt.

Berg and Hudson (1992) have argued that sharp dividing lines between the traditional sector and the modern sector are inappropriate; that even within cotton, the most dynamic industry, there were large islands of traditional domestic production which actually grew as a result of mechanisation elsewhere. On the other hand, some service industries such as land transportation before 1830 were experiencing productivity growth without much dramatic technological progress. Such refinements do not weaken the arithmetic power of the argument unless the relative sizes of the two sectors are radically revised. More serious is the critique that this exercise assumes that the rates of growth are independent. Much as is true today for today's high-tech sector, this independence seems unlikely because of input–output relations between the different sectors. If the 'modern sector' during the Industrial Revolution helped produce, for

[2] All the same, Crafts and Harley explicitly deny adhering to a school that would negate the profound changes that occurred in Britain during the Industrial Revolution and restate that 'industrial innovations . . . did create a genuine industrial revolution reflected in changes in Britain's economic and social structure', even if their impact on economic growth was more modest than previously believed (1992: 3).

[3] Even if changes in the modern sector itself were discontinuous and its growth rate very high, its small initial size would limit its impact on the economy-wide growth rate, and its share in the economy would increase gradually. In the long run, the force of compound growth rates was such that the modern sector swallowed the entire economy. How long was the long run? A numerical example is illuminating here. Suppose there are two sectors, a modern one growing at 4 per cent per year and a traditional one growing at 1 per cent per year, and suppose that initially the modern sector produces only 10 per cent of GNP. It will therefore grow relative to the economy as a whole, but it will take seventy-four years for the two sectors to be of equal size and a full century after the starting point the traditional sector will have shrunk to about 31 per cent of the economy. These hypothetical numbers fit the actual record rather well.

instance, cheaper and better iron, that would have affected the tools used by farmers and artisans who otherwise would belong to the slow-growth part of the economy. Devices, materials and ideas from the modern sector slowly penetrated into the traditional industries, and some of them, such as steam power, seem in many ways similar to the modern notion of General Purpose Technology (Helpman 1998).

The exact limits of the 'modern sector' remain in dispute, since industry-specific output and productivity statistics do not exist. Temin (1997) has maintained that the Crafts–Harley 'minimalist' argument is inconsistent with the patterns of British foreign trade, which clearly show that Britain maintained a comparative advantage not just in the few rapidly expanding 'new industries' but in a host of small, older industries such as linen, glass, brewing, pottery, buttons, soap, candles, paper, and so on. Temin relies on export figures to make a point about comparative advantage and to infer from it indirectly that technological progress occurred on a variety of fronts or at least that the input–output effects from the technologically dynamic sectors to the laggards were significant. Anecdotal evidence and examples of progress in industries other than the paradigmatic high-flying industries can be culled from specialised sources.[4] On the other hand, as critics have pointed out, maintaining comparative advantage is not the same as attaining rapid productivity growth. Moreover, the growing reliance on imported food would have implied higher manufacturing exports even in the absence of technological progress in the industrial sector (Crafts and Harley 2000). Even with the sectors that Temin believes to be progressive, the modern sector would still include only a relatively small proportion of GNP and employment in 1760 or even 1800.

The sense in which technological progress is supposed to have led to economic growth is through efficiency-increasing innovation. By that it is understood that a given quantity of output or GNP can be produced with fewer inputs and thus the economy becomes more productive. A growth in efficiency is not a necessary condition for *economic* growth. Income per capita could increase through a rise in the capital/labour ratio, or through a rise in diligence through longer work-years and higher participation rates. In a pair of pathbreaking papers Jan de Vries (1993, 1994) has argued for an 'industrious revolution' in which more household members participated in market activities (which get counted as part of GDP) and replaced goods produced in the household by goods purchased in the market. Voth (2001) has confirmed this increase in diligence, although it is complicated by changes in the age structure of the

[4] On the hardware industry, see Berg (1994: ch. 12). On many of the other industries, classic industry studies carried out decades ago have not yet been supplanted such as Coleman (1958) on the paper industry, Mathias (1953, repr. 1979a) on brewing, Clow and Clow (1952) and Haber (1958) on the chemical industries, Church (1970) on the shoe and boot industry, McKendrick (1961, 1982b) on potteries, and Barker (1960) on glass.

population (Britain was, on average, getting younger during the years of the Industrial Revolution). On the other hand, an economy that experiences persistent total factor productivity growth is likely to experience per capita income growth.

Economists have remained loyal to total factor productivity (TFP) analysis, perhaps more than the concept deserves. The idea is to look at the productivity of all inputs, because a growth in that of one factor, say labour, could occur simply as the result of a growth in the level of complementary factors that make it work more efficiently. The literature on the calculation of the residual is enormous, and this is not the place to sing its praises or to criticise it. The actual logic is to subtract a weighted sum of input growth from output growth, and to define the 'residual' as productivity growth. An equivalent procedure is to use the 'dual' approach, estimating the growth of weighted real returns to factors (McCloskey 1981; Antràs and Voth, 2003). In order to identify these numbers as a correct approximation of total factor productivity, we need to assume perfect competition, constant returns to scale, the correct identification of the production function, and Hicks-neutral technological change.[5] Without that, the use of factor shares as proxies for the elasticities of output with respect to inputs would no longer hold.[6] Any errors, omissions, mismeasurements and aggregation biases that occur on either the output or the input sides would, by construction, be contained in the residual. For instance, we simply do not know much about the flow of capital services and their relationship to the stock of capital. If horses or machines worked longer hours or factory buildings were occupied for more than one shift, it is unlikely to be registered in our estimates as an increase in capital inputs. Even if properly measured, the identification of total factor productivity growth with technological progress requires the suspension of disbelief on a number of fronts, above all as far as the quality of the data is concerned.

The best-known attempts to compute total factor productivity for Britain during the Industrial Revolution were made by Crafts and Harley. Between 1760 and 1800, Crafts and Harley estimate, total factor productivity 'explained' about 10 per cent of total output growth; in the period 1801–31 this went up to about 18 per cent. This seems rather unimpressive, but it should be kept in mind that growth is concerned with output per worker (or per capita). If we look at output per worker, we observe that for the period 1760–1830 practically the entire growth of per capita income – such as it was – is explained by technological change.

[5] Hicks-neutral technical change leaves the marginal rate of substitution between any two inputs unaffected by the technological change, and thus the relative contribution of each input to the production process is unaltered.

[6] As Antràs and Voth (2003), in the most recent contribution to this literature, point out, whatever weaknesses are embodied in the primal approach will be entirely reflected in the dual as well.

Table 1.2 Total factor productivity, computed from product accounts

	Per capita growth	Contrib. of capital/ labour ratio	Contrib. of resources per capita ratio	Total contrib. of non-labour inputs	Total factor productivity growth	Productivity as % of total per capita growth
1760–1800	0.2	0.2*0.35 = 0.07	−0.065*0.15 = −0.01	0.06	0.14	70
1800–30	0.5	0.3*0.35 = 0.105	−0.1*0.15 = −0.015	0.09	0.41	82

Source: Computed from Crafts 1985a: 81 and Crafts and Harley 1992: table 5.

The contribution of total productivity towards per capita output are presented in Table 1.2, where the standard ('primal') procedure is used, and Table 1.3 where the dual procedure is used. Both procedures require making assumptions about the shares of labour, capital and land in national income. The shares used are labour 50 per cent, capital 35 per cent, land 15 per cent. These figures were originally proposed by Crafts based on computation made by Deane and Cole who estimated the share of labour in national income to be 44 per cent in 1801 and 49 per cent in 1860. Crafts notes that the 44 per cent figure seems low, and his proposed adjustment seems uncontroversial. While the computation of the primal is not sensitive to misspecifying the shares of labour and capital (which grow at similar rates between 1760 and 1830), the share of land matters since resources were growing at a much slower rate than labour or capital (and hence if the share of land used is too low, the estimate of total input growth would be biased upward and that of total productivity would be biased downward).

To judge from Tables 1.2 and 1.3, British economic growth was slow in this period, but what little there was seems to be explained by the residual. The assessment of the importance of TFP in the critical period 1770–1800 is difficult because it relies on the division of one small growth rate by another, and because a lot depends on the inclusion of the government (which extracted a large amount of income in terms of higher taxes). Until 1830, however, the increase in TFP is about equal to the growth in product per capita: for the entire period 1770–1860, product per capita increased at an average rate of 0.6 per cent per year, of which 0.41 (or almost exactly two thirds) is explained by Antràs and Voth's estimates of total productivity growth. Because all numbers are small, however, this result is rather sensitive: a ratio of two numbers very close to zero rarely produces a robust result. Even a minor revision in computation means a major difference in the conclusions. By varying their sources for capital and resource income growth, Antràs and Voth show that productivity growth either could be made negative or could over-explain income per capita growth. Furthermore, just by varying the assumptions on factor shares (the most assumption-driven part of the calculation) total factor productivity growth could be made to vary from 0.18 per cent to 0.38 per cent in 1770–1800, and between 0.24 per cent and 0.46 per cent in 1830–60 (the difference in 1800–30 is smaller).

Table 1.3 Total factor productivity, computed from income accounts							
'Preferred estimates':		Total factor productivity growth					
	Per capita output growth	capital income	labour income	land income	Total private sector	Government	TFP growth
1770–1801	0.2	−0.40*0.33 = −0.132	0.35*.45 = 0.157	0.26*0.14 = 0.036	0.061	2.60*.08 = .208	0.27
1801–31	0.5	0.71*0.33 = 0.234	0.25*0.45 = 0.112	0.76*0.14 = 0.106	0.452	1.11*.08 = .088	0.54
1831–60	1.1	−0.21*0.33 = −0.069	0.68*0.45 = 0.306	0.48*0.14 = 0.067	0.304	0.31*.08 = .025	0.33
Sensitivity analysis:							
1770–1801 <lower bound, upper bound>[a]							<−0.09, 0.64>
1801–31 <lower bound, upper bound>[b]							<0.48, 1.26>
1831–60 <lower bound, upper bound>[c]							<0.31, 1.26>

Source: computed from Antràs and Voth 2003.

Notes:
[a] minimum: using Clark 'charity returns'; maximum: using Lindert–Williamson price index.
[b] minimum: using Clark 'charity returns'; maximum: using wholesale price index.
[c] minimum: using Clark 'real rents'; maximum: using Lindert–Williamson price index.

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Table 1.4 The world according to Clark, all in average percentage change per year

	Real per capita GDP growth	Total factor productivity growth	TFP growth attributable to cotton and wool alone	TFP attributable to other sectors
1760–1800	−0.05	0.04	0.21	−0.17
1800–30	0.58	0.68	0.30	0.38
1830–60	0.13	0.20	0.27	−0.07

Source: Clark 2001b.

The most robust conclusion that the recent literature offers is that, as far as it can be measured, there was little total factor productivity growth at the aggregate level during the classical Industrial Revolution. This conclusion seems unsurprising, since a very slow per capita growth is irreconcilable with rapid TFP growth unless there is dramatic decumulation of capital or a reduction in natural resources.[7] Precisely because growth per capita was so slow and there is little to explain, small differences in procedures and estimation will produce radically different residuals.[8]

A different approach to the same issues is proposed by Gregory Clark (2001b). Clark has employed the data he has collected from the charities commission to revise the growth of real per capita GDP between 1760 and 1800 and finds it to be essentially zero. After 1800 there was some recovery, but then his data show a sudden and unexpected slow-down after 1830. Clark's conclusions are still tentative, but because he uses new sources they should be noticed. In this line of work, an ounce of new evidence is worth a pound of theory, but the representativeness of samples and the calculation of proper price indices remain difficult questions, especially when they fly in the face of other evidence.

On the basis of the data summarised in Table 1.4, Clark dismisses the entire Industrial Revolution as a historical phenomenon, and takes exception to the Berg–Hudson–Temin view of a broad-based set of technological advances. The very slow growth he observes for the decades after 1830 (much slower than for the 1800–30 period) seems to fly in the face of much other historical evidence and must be regarded as preliminary. It is also somewhat odd that in these calculations TFP growth consistently *over*explains per capita income growth. This difference is not quite impossible (for instance, capital/labour ratios could be declining or the

[7] In an open economy, there could also be a dramatic decline in the terms of trade that would be consistent with a possible situation of widespread technological progress without growth (so that the economy has to produce more for the export sector to pay for ever more expensive imports). Such a decline would also bias the estimated TFP growth in the dual procedure downward, and a correction for this after 1800 does increase the estimated value of TFP growth from 0.49 per cent per year to 0.61 per cent.

[8] For instance, Voth (1998, 2001) has radically revised labour inputs and claimed that because labour input per capita increased in the fifty years before 1800, the residual is extremely small and possibly negative.

labour-year might have become shorter), but for this period these explanations seem inapplicable: capital grew slightly faster than labour and, as we have seen, the labour year grew, if anything, longer. All the same, Clark's data confirm the overall picture of slow pace of growth during the Industrial Revolution, and that what growth occurred is attributable to total factor productivity.

Moreover, recent attempts to improve our estimates of the inputs that went into the production function seem to indicate that those estimates are still too conservative. For instance, if Voth is correct about people working longer hours and the quantitative importance of the decline of St Monday (see p. 277), labour inputs estimated from population data *under*estimate labour inputs and thus overestimate productivity growth. Clark (2001b) has re-examined the housing and real estate market, always one of the weakest links in the computation of the income accounts, and discovered that the property income estimates based on the property tax of 1803 seriously underassessed the value of land and houses, and as a result the rise of this component of income in the following decades is seriously overstated. Real rental income per capita by this account actually fell from the late eighteenth century to the middle of the nineteenth. Given that population almost tripled in this period, that is not an implausible finding, especially in view of the growing dependence on the importation of land intensive products. If correct, the computations of income per capita growth are *over*estimated and so are productivity computations derived from them.

It is not only that income per capita and productivity grew slowly, but what little growth there was, argues Clark, was due to a set of adventitious circumstances.[9] The advances in textile technology, in his view, happened to occur in a large sector with an elastic demand, and much of the rest of the economy was not really affected until the closing third of the nineteenth century. This ultra-narrow view of the Industrial Revolution resonates strangely with the 'energy-interpretation' that regards the invention of steam engines and the emergence of the capability to convert stored-up (fossil) energy into work as the macroinvention that changed all (Cipolla 1965; Wrigley 2000; Goldstone 2002). Yet the energy interpretation is too narrow itself. What the aggregative accounting approach conceals is what went on inside people's minds, which prepared the ground and planted the seeds of what was to come. The years 1760–1815 witnessed more than just some lucky breaks in a handful of industries: it was also the period in which people defied gravity through hot-air balloons, began the conquest of smallpox, and learned to can food, to use binary codes for manufacturing purposes, to infer geological strata from fossil

[9] The idea that the Industrial Revolution was in some sense a fortunate 'accident' or at least highly contingent was first proposed by Crafts (1977). For a recent argument along those lines see Goldstone (2003).

evidence and to burn gas for lighting. They advanced and improved old and tried techniques as much as they introduced radical new ones. Not just steam but water power, too, was greatly improved.[10] The invention of stearic candles kept an old technology thriving despite the threats from new sources of light. In pottery, one of the oldest techniques known to mankind, Josiah Wedgwood and others introduced new materials, new moulding techniques and improved oven-firing. It may well have been inevitable that the time it took for these improvements to filter through enough barriers to affect national income is longer than was thought in the past. Indeed, it seems surprising that it could have been thought otherwise. But that does not reduce the achievement. As McCloskey (1981: p. 118) put it, the Industrial Revolution was not the Age of Cotton, nor the Age of Steam; it was an age of improvement.

Yet, as noted, improvement was not ubiquitous. Large sectors of the economy, employing the majority of the labour force and accounting for at least half of gross national product in 1830 were, for all practical purposes, only little affected by innovation before the middle of the nineteenth century. Even in textiles, the finishing industries such as tailoring, haberdashery and millinery remained largely manual until the advent of the sewing machine in the 1860s. Domestic servants, construction workers, retailers, teachers, sailors and dockworkers, to pick a few examples, were but little affected. Some industries changed and others did not, for reasons that in part reflected the demand side of the economy or the supply of raw materials and energy, but above all had to do with technological capabilities. Yet we should also recognise that some of the inventions, especially in energy, engineering and materials, found applications in many industries, and that general purpose technologies spread throughout the economy.

What makes the use of national accounts particularly difficult as a measure of economic progress is that further refinements of the total factor productivity computation are yielding ambiguous results and require data that are not available on an aggregate level. On the one hand, economists have increasingly realised that rapid technological progress implies both product and process innovation. The appearance of new products and their growing availability, and improvements in the quality of existing ones, would not show up in the output statistics. In that regard, perhaps, the first Industrial Revolution was less problematic than the second, since most of the major breakthroughs were process innovations. The improvements in cotton quality and variety introduced perhaps the most significant large-scale bias of this sort (Cuenca 1994: 78), but the

[10] In Britain, the greatest names in the improvements in water power were John Smeaton and John Rennie. They designed the so-called breast wheel that combined the advantages of the more efficient overshot waterwheels with the flexibility and adaptability of the undershot waterwheel. The increased use of iron parts and the correct setting of the angle of the blades also increased efficiency. The great French engineer Poncelet designed the so-called Poncelet waterwheel using curved blades, and theoretical hydraulics gradually merged with the practical design of waterwheels.

possible impact of the mismeasurement implied on changes in economic performance has not been addressed. In so far as technological advances increase consumer surplus or some other indicator of utility, all measures of economic growth during the 1760–1830 years miss the invention of the smallpox vaccination process. Vaccines became available right at the midpoint of the 'classical' Industrial Revolution period (1796). What economist would deem that invention 'insignificant'? In other words, the computed residual *under*states the economic significance of technological change simply because the procedures used miss the introduction of new products and improvements in quality.[11] Economists interested in a true welfare measure of technological change should try to estimate growth in social surplus. This counterfactual mental experiment asks how much of GNP would consumers who enjoyed a certain invention have been demanding to be paid to do 'without'. Applied to steam power, as Von Tunzelmann showed in 1978, this may not have been all that much because water power provided an alternative. Of course, as we have seen, water power itself was improving dramatically during the same period, and hence the social savings calculations understate the gains from steam power compared to 1750 (as opposed to a hypothetical world of 1830 without steam). Yet even beyond that, the calculation must leave some pessimists uncomfortable. How much, for example, would someone who did not have access to anaesthesia (introduced in surgery in the 1850s) be willing to pay to have it? All the same, using the standard definitions of national income accounting, it seems unlikely that new product and quality improvements would radically change the computations reported above simply because there were few new products by comparison with the late nineteenth century.

The apparent dominance of invention over abstention suggested by total factor productivity analysis, once one of the most striking findings of the New Economic History, seems somehow less secure now than it did in the 1990s. Most of the payoff to technological creativity occurs in a more remote future and is spread over a longer period than was previously believed. Despite the fragile nature of many of the estimates, the conclusion that seems to emerge is that in the closing decades of the eighteenth century, the classical period of the Industrial Revolution, the changes in technology and organisation, however pregnant of future change, were insufficient to affect broad measures of the overall economy. After 1800, and especially after 1820, these effects became more noticeable, but their impact on aggregate variables was inevitably gradual and slow.

[11] There are other examples indicating qualitative improvements in this period. One of those was recently emphasised by Nordhaus (1997) in a paper arguing that the history of lighting suggests that product innovation may be the cause of a radical understatement of the advantages of technological progress. Among the important innovations introduced in this time was the Argand oil lamp, invented in the 1780s, and of course the introduction of gas lighting in the first decades of the nineteenth century.

EXPLAINING THE INDUSTRIAL REVOLUTION

None of the above reduces the significance of the Industrial Revolution. What has come under attack is the view, suggested originally by Deane and Cole in 1967, that the Industrial Revolution *itself* was a period of rapid economic growth. Instead it may be better regarded as a period of incubation in which the groundwork to future growth was being laid. Such preparation is historically important because without it we cannot possibly understand how Europe managed to break out of the negative feedback cycle of recurring episodic growth followed by retrenchment that had characterised economies before 1750 both in Europe and elsewhere.

Explaining the sudden change from a world of slow growth to one in which expansion became the norm has remained a central issue in modern scholarship. Before we can 'account' for the Industrial Revolution, some underbrush needs to be cleared.

The first point is that the industrial revolution in its wider sense was not really a British affair but a European (or perhaps north Atlantic) event. One interpretation has suggested that without Britain's leadership it might not have happened at all (Wrigley 2000; Goldstone 2003). Eric Jones (1987) has called this 'the little Englander' view of economic history. It is true, of course, that the first signs that something dramatic was brewing emerged in Britain, and that by 1820 much of the rest of Europe in some way felt 'left behind'. But Britain's primacy is a different-order problem and has a different historical explanation than the dramatic advance of Europe over the rest of the world. Confounding these two issues could lead to misleading conclusions. For instance, Pomeranz insists that the reason that the Industrial Revolution occurred in Europe but not in China was the access to coal and the 'ghost acreage' that Europe derived from its colonies. But coal was as localised in the north Atlantic as it was in China, and some regions such as Switzerland and New England were able to substitute around it by choosing low-energy-intensive industries and using alternative sources such as water power or peat. An industrial revolution led by continental economies would have been delayed by decades and differed in some important details. It might have relied less on 'British' steam and more on 'French' water power technology and 'Dutch' wind power, less on cotton and possibly more on wool and linen. But given the capabilities of French engineers and German chemists and the removal of many institutions that hampered their effective deployment before 1789, it would have happened. Even without Britain, by the twentieth century the gap between Europe and the rest of the world would have been there (Mokyr 2000).

Technological change is not just a 'residual' or a shift in an isoquant. It is something that takes places inside a human mind and from there is mapped successfully onto an object, a substance or an action. The 'mind' part is especially crucial. The intellectual foundations of the technology which made the Industrial Revolution came out of the Enlightenment, the scientific advances of the seventeenth and eighteenth centuries, the Renaissance, the Reformation and the printing press. These were all pan-European phenomena, and while Britain was an active participant and then became a leader, the reasons for its position were in a different class from those that explain the deeper historical roots of the phenomenon altogether.

Second, what made the Industrial Revolution such a watershed phenomenon was not just the dramatic inventions of Watt, Smeaton, Harrison, Cort and Crompton during the years of *Sturm und Drang* (approximately 1760–1800). Dramatic inventions before the Industrial Revolution were not unknown in Europe or elsewhere. Some of these breakthroughs undeniably had an effect on growth, such as the invention of the spinning wheel and the horizontal loom in the twelfth century, or that of the blast furnace and navigational and shipbuilding technology in the fifteenth. The increased industrial use of coal as a source of heat for industry and improvements in agricultural productivity (in part owing to investment in land improvements and livestock rather than technological change) did lead to higher income per capita and the ability to sustain a larger population on a given resource base (Wrigley 2000). But none of these 'episodes' resulted in sustainable per capita growth, even if each time they ratcheted living standards up to a higher level. Each of these episodes created a negative feedback effect that eventually eliminated growth. Identifying such feedback effects in earlier periods, and then checking whether they may have weakened or even turned positive may provide a better understanding of what happened.

The critical period in which West and East diverged may thus have been not the classical years of the Industrial Revolution but the decades that followed. Attention may have been diverted away from post-1815 developments by the spectacular inventions of the *annus mirabilis* as Donald Cardwell (1972) has termed the year 1769. In other words, what made the Industrial Revolution into the 'great divergence' was the *persistence* of technological change after the first wave. To see this, we might well imagine a counterfactual steady state of throstles, wrought iron and stationary steam engines, in which there would have been a one-off shift from wool to cotton and from animate power to stationary engines. But this is not what happened: the true miracle is not that the classical Industrial Revolution happened, but that it did not peter out like so many earlier waves of innovation. It was followed after 1820 by a secondary ripple of inventions that may have been less spectacular, but these were the ones that provided the muscle to the downward trend in production costs, spread the application to new and more industries and sectors, and eventually showed up in the productivity statistics.

Among those we may list the perfection of mechanical weaving; the invention of Roberts's self-acting mule in spinning (1825); the extension and adaptation of the techniques first used in cotton to carded wool and linen; the continuing improvement in the iron industry through Neilson's hot blast (1829) and other inventions; the continuing improvement in steam power that kept raising the efficiency and capabilities of the low-pressure stationary engines, while introducing the high-pressure engines of Trevithick, Woolf and Stephenson; the breakthroughs in engineering and high-precision tools by Maudslay, Whitworth, Nasmyth, Rennie, Brunel and the other great engineers of the 'second generation'; the growing interest in electrical technology leading to electroplating and later to the telegraph; the continuous improvement in crucible steelmaking through co-ordinated crucibles (as practised for example by Krupp), the work of Scottish steelmakers such as David Mushet (father of Robert Mushet, celebrated in one of Samuel Smiles's *Industrial Biographies*), and the addition of manganese to crucible steel known as Heath's process (1839). These advances – always excepting the telegraph – were in the nature of microinventions, but they did not run into diminishing returns nearly as fast and as early as they had before.

How, then, do we account for the Industrial Revolution? The literature has identified a number of themes around which the transition can be explained. But, as noted, it is important to separate out the 'little' question of why Britain was first from the 'big' question of why there was an Industrial Revolution in the West. The former is no mean question either, but from the point of view of the global economy it is the lesser one. I have dealt with the question of 'why Britain first' elsewhere (Mokyr 1994, 1998) and for a detailed discussion the interested reader is referred there. Little has been done in recent years to weaken the view that Britain's advantages were real, but it seems now agreed upon that they were to some extent temporary if not adventitious. Its ability to stay out of military conflicts on its own soil, a political system that was capable of reinventing itself and introducing reforms without violence, a capitalist, productive and progressive agricultural sector, an institutional agility that allowed it to adapt to a changing environment, all must be at the top of any such list. Britain was spared the upheavals of the French Revolution and its subsequent disruptions, even if it had to bear substantial financial costs of the Wars. Its closest continental rivals, the Low Countries, France and the western parts of Germany, were by contrast severely affected.

Furthermore, Britain could rely on a class of trained artisans and mechanics who were capable of carrying out clever designs and actually making things that worked and were still affordable. What Britain had in relative abundance is what Stevens (1995) has called 'technical literacy', which required, in addition to literacy, a familiarity with the properties of materials, a sense of mechanics, and the understanding of notation and spatial-graphic representation. Technical competence was a major factor in the leadership role that Britain played in the Industrial Revolution. Explaining this ability harks back in part to economics and in part to natural endowments: Britain already had a relatively large proportion of people in non-agricultural activities, both full-time artisans and part-time in cottage industries. It had a shipbuilding industry, a mining sector and a developed clock- and instrument-making sector. Smeaton, Watt, Ramsden, Harrison, Murdoch, Trevithick and so many other successful inventors of the time possessed the complementary skills needed for successful invention, including that ultimate umbrella term for tacit knowledge we call 'dexterity'. In the little workshop he used as a teenager, John Smeaton taught himself to work in metals, wood and ivory and could handle tools with the expertise of a regular blacksmith or joiner (Smiles 1891). What made the difference between a James Watt and a Leonardo was that Watt had Wilkinson and Leonardo did not. Britain by no means monopolised these skills: the millwrights of the Zaan area in the Netherlands and French engineers and craftsmen such as Jacques de Vaucanson and Honoré Blanc were obviously as competent as anyone Britain had to offer, and Smeaton himself travelled extensively to the continent to study these techniques. Yet Britain had more of them, and British society channelled their creative energies to those activities that were most useful to future technological development in the eyes of that most discerning of all masters: the market.

In Britain, these skills were transmitted through an apprenticeship system, in which instruction and emulation were intertwined, and thus codifiable and tacit knowledge were packaged together. Engineers worked for the private sector, not for the state, and thought mostly in terms of profit and economic efficiency. As long as the application of the technology did not require a great deal of formal knowledge, this system worked well for Britain. Britain also benefited from a social elite with an unusual interest in technical improvement, its ability and willingness to absorb and apply useful ideas generated elsewhere (without the 'not invented here' kind of arrogance), a well-functioning transport system favoured by nature and improved by investment, and the propitious location of some resources, especially coal. None of those factors was necessary or wholly unique to Britain, and while their fortunate conjuncture in Britain helped Britain secure its leadership, they do not explain the Great Divergence.

THE INTELLECTUAL ORIGINS OF ECONOMIC GROWTH

What made modern and sustained growth possible was the weakening of the negative feedback effects that had restrained economic expansion before 1750. Some of these feedbacks may even have switched sign and become positive. To make such an interpretation more than a tautology, we need to specify their nature in more detail. Many scholars following the work of Douglass North and Mancur Olson have insisted that modern growth became possible because of institutional changes that reduced the opportunities for rent-seeking behaviour. The decline of arbitrary taxation and state enforced monopolies (excepting patents), the gradual emergence of freer trade, the weakening and eventual abolition of guilds, the streamlining of the legal environment in which economic activity took place, and the growth of personal safety and contract enforcement through courts must have had an effect on the dynamic behaviour of the economy. From 1688 to 1848, institutional change in the western world was trending in these directions, haltingly and hesitantly perhaps, but the move was unmistakable. In this way the political enlightenment and the institutional changes it inspired brought about a more liberal environment, in which the kind of parasitic and predatory behaviour that had hamstrung growth before gradually weakened. This movement over time reached deeper and deeper into the darker institutional corners of eastern and southern Europe, but it started in Britain and the Low Countries.

The negative feedback from classical demographic response also changed. E. A. Wrigley (1988, 2000) has pointed out that the transition from a land-based or 'organic' to an 'inorganic' (mineral) economy is key to the understanding of the dissolution of the Malthusian dynamic. There is no doubt that economic performance at all times depends on the way the economy deploys energy and materials. The growing role of fossil fuels and iron was the defining characteristic of the first Industrial Revolution just as the use of steel and electric power characterised the second industrial revolution. In both cases this rising consumption of energy and materials clearly implied that the classical relation of diminishing returns to the fixed factor no longer held in its old form. It also seems plausible, as some economists have argued (Galor and Weil 2000; Galor and Moav 2002; Lucas 2002) that profound changes in demographic behaviour were driven by changes in the desired number of children. The logic here is based on a growth in the return to human capital, which makes it more attractive to have fewer children but invest more in their education. The eventual result was a sharp decline in fertility rates, driving up per capita income. Moreover, classical models inspired by Malthusian thinking implicitly assumed closed economies. Land was fixed in these models and they were driven by diminishing returns to the fixed factor. The growing access of the industrialising world to 'ghost acreage' (land and mineral resources located at a considerable distance from the final consumer, whether in the same political unit or not) obviated the old models. Countries with rapidly growing population did not starve – they imported food.

All the same, many of these changes were in their turn driven by changes in knowledge. We cannot possibly understand the transition to a mineral economy without realising the extent to which resources and knowledge were complementary. The coal that Britain dug out of its land had been there all along, but only in the seventeenth century was it applied to a wide variety of industrial uses, and only in the eighteenth century could it convert its natural form of energy (heat) to kinetic energy and thus do 'work'. Locating coal seams, digging it out of the ground and transporting it to its markets are complex activities. The demographic changes were similarly driven in part by variables that depended on useful knowledge. The rise in the rate of return to human capital and the rising effectiveness of contraceptive technology both belong to that category. If we are to search for a clue as to what really made the difference, we should look at what people knew, who knew what was known, how others had access to it, and how knowledge expanded both in terms of more being known and in terms of making what was known more accessible.

The Industrial Revolution, then, was driven by an expansion of technology or 'useful knowledge', in the classic sense formulated by Nobel prize winner, economist Simon Kuznets. Technology, after all, is the manipulation of natural regularities and phenomena in the service of our material well-being. To observe and register such regularities does not require that they be wholly 'understood'. But *something* has to be known. The most obvious example is the steam engine. Much of the physics that explained why and how steam power worked the way it did was not established until the middle of the nineteenth century and was certainly not available to Newcomen or Watt. But the idea of an atmospheric device that converts heat into work did require the notion of an atmosphere and atmospheric pressure, and the realisation that a vacuum creates the opportunity of moving a piston with force.[12] This is not a plea for technological determinism. On the contrary, the argument is that technology itself depended on the existence of a minimum amount of knowledge. Moreover, how much and what kind of knowledge was generated and what was done with it was a function of institutions. Technology could open a door, but it could not force a society to walk through it.

The continuation of technological progress at an accelerating pace in the nineteenth century depended on a phenomenon that pervaded much of the western world in the seventeenth and eighteenth centuries and which, failing a better term, I have termed the *Industrial Enlightenment* (Mokyr 2002). What I mean by that is a number of related phenomena, all of them quite novel (in extent, if not entirely in their essence).

First, the scientific developments of the seventeenth century mark an important foundation of the Industrial Enlightenment, despite the

[12] Similarly, the invention of chlorine bleaching required, at the very least, the knowledge of the existence of chlorine – discovered in 1774 by a Swedish chemist named Scheele. Of course, there was still a lot to be learned: Scheele and Berthollet still believed chlorine to be a compound, and its true nature as an element was shown by Humphry Davy in 1812.

often-repeated truism that before the 1780s there was little in the actual knowledge of natural philosophers that was of much direct use to people in production. This takes too narrow a view of the achievements of the great minds from Copernicus to Newton. Beyond their specific discoveries, they basically persuaded themselves and growing portions of the world around them that nature was 'rational' and followed knowable laws and regularities. Such knowledge should be open and made widely available (as opposed to more narrow technical knowledge which often remained private). A penchant for secrecy and privacy had characterised medieval alchemists, astrologers, botanists, geographers, and so on. This secrecy made room for a knowledge culture in which publicity and fame were rewarded and priority conveyed prestige (Eamon 1994).

The Industrial Enlightenment sought to understand why techniques worked by generalising them, trying to connect them to the formal propositional knowledge of the time. These would lead to extensions, refinements and improvements, as well as speed up and streamline the process of invention. This idea eventually penetrated the 'useful arts'. Important technical books in fields from mining techniques to botany were increasingly written in the vernacular or translated. The arrangement of topics either alphabetically (in technical dictionaries and encyclopaedias) or by topic (in technical manuals and descriptions of arts and crafts) created 'search engines' that made knowledge more accessible. A great effort was made to survey and catalogue artisanal practices out of the dusty confines of workshops, to determine which techniques were superior and to propagate them. The best-known example is Diderot's justly famous *Encyclopédie*, the epitome of Enlightenment literature, with its thousands of very detailed technical essays and plates (Headrick 2000).[13] Encyclopaedias were supplemented by a variety of textbooks, manuals and compilations of techniques and devices that were (or could be) in use somewhere. In machinery and in dyeing technology, to pick two examples, comprehensive treatises tried to catalogue and fully describe every technique known at the time.[14] Graphical representation and a standardisation of notation and units of measurement made the transfer of knowledge more efficient. Moreover, access to technical knowledge became in part a market

[13] In the *Encyclopédie*, in his article on 'arts', Diderot himself made a strong case for the 'open-ness' of technological knowledge, condemning secrecy and confusing terminology, and pleading for easier access to useful knowledge as a key to sustained progress. He called for a 'language of [mechanical] arts' to facilitate communication and to fix the meaning of such vague terms as 'light', 'large' and 'middling' to enhance the accuracy of information in technological descriptions. The *Encyclopédie*, inevitably perhaps, only fulfilled these lofty goals very partially and the articles on technology varied immensely in detail and emphasis. For a recent summary of the work as a set of technological representations, see Pannabecker (1998).

[14] The redoubtable Andrew Ure published his *Dictionary of Arts, Manufactures and Mines* in 1839 (an earlier edition, dedicated mostly to chemistry, had appeared in 1821), a dense book full of technical details of crafts and engineering covering over 1,300 pages of fine prints and illustrations, which by the fourth edition (1853) had expanded to 2,000 pages.

phenomenon: over-the-counter knowledge became available from experts such as civil engineers, coal viewers and other consultants.

Moreover, the ideology and rhetoric of natural philosophy changed. Aristotelian science had set as its main purpose to 'understand' nature. During the scientific revolution and the eighteenth century the idea that the purpose and the justification of the search for natural regularities was to harness and exploit them, as Bacon had argued, kept gaining ground. In the days of Bacon, the notion that useful knowledge was to be exploited for material improvement was more hopeful than realistic, and even for the founders of the Royal Society the idea was in large part a self-serving device for lobbying rather than a sincere objective. Yet, the Industrial Revolution eventually proved them right: after 1800, useful knowledge became the dynamic force that Bacon had hoped for.[15]

The Industrial Enlightenment was characterised by an attempt to expand what was known and therefore what would work. For decades, the role of useful knowledge in the Industrial Revolution has been dominated by long debates about the 'role of science' in which minimalists such as David Landes (1969) and Rupert Hall (1974) debated Musson and Robinson (1969). It is hard to disagree with Shapin (1996: 140–1) that 'it appears unlikely that the "high theory" of the Scientific Revolution had any substantial direct effect on economically useful technology either in the seventeenth century or in the eighteenth . . . historians have had great difficulty in establishing that any of these spheres of technologically or economically inspired science bore substantial fruits'. Yet the methods of scientific endeavour spilled over into the technological sphere: concepts of measurement, quantification and accuracy, which had never been an important part of the study of nature, gradually increased in importance.[16] The precision skills of the clockmaker blended with the scientific and mathematical rigour of the post-Galileo natural philosopher were personified in key figures such as Christiaan Huygens, who perfected the pendulum clock and also sketched the first internal combustion engine. His assistant, Denis Papin, built the first model of an atmospheric engine. The 'ideology of precision' influenced later key figures such as James Watt, John Smeaton and John Harrison, whose contributions to economically significant inventions are not in doubt. Quantification, measurement and a sense for the orderly arrangement of information into what we today would call 'data' constituted one of the most precious gifts that science gave to technology (Heilbron 1990; Headrick 2000).

[15] The relation between pre-Lavoisier chemistry and the Industrial Revolution is particularly enlightening, since it was widely believed that 'chemical philosophy' would help to advance agriculture, manufacturing and medicine. Yet in the eighteenth century, this remained, in the words of the leading scholar on the topic, 'more of a promissory note than a cashed-in achievement' (Golinski 1992).

[16] The noted historian of science Alexandre Koyré (1968) argued that the scientific revolution implied a move from a world of 'more or less' to one of measurement and precision.

The intellectual background of the Industrial Revolution is thus more complex than the ability of natural philosophy to provide *direct* insights into the natural regularities and phenomena that could be applied in a straightforward manner. The unintended spillover of the flourishing of natural philosophy in the seventeenth century was the creation of a 'scientific culture', as Margaret Jacob (1997, 1998) has called it. The widespread interest in physics, chemistry, mechanics, botany, geology and so on created a technical literacy she feels was at the root of the innovations that made the Industrial Revolution. The Industrial Enlightenment spawned figures for whom the economic promise of bridging between natural philosophy and the practical and mechanical arts was axiomatic. One thinks of Dr John Roebuck, a physician and iron-monger, early supporter of James Watt's improvements to the steam engine, and inventor of the lead process in the manufacture of sulphuric acid, or of Joseph Black, the Scottish chemist and friend of James Watt. For progressive industrialists such as pottery maker Josiah Wedgwood, reliance on scientists (such as his close friends Erasmus Darwin and Joseph Priestley) was essential (McKendrick 1973). Others, such as Leeds woollen manufacturer Benjamin Gott, read French chemistry books applicable to his dyeing business.

The formal institutional manifestations of this culture are well known. The many scientific and philosophical societies created contact and interaction between the people who knew things and those who were hoping to apply that knowledge. The Society of Arts, a classic example of an access-cost reducing institution, was founded in 1754, 'to embolden enterprise, to enlarge science, to refine art, to improve manufacture and to extend our commerce'. Its activities included an active programme of awards and prizes for successful inventors: over 6,200 prizes were granted between 1754 and 1784. Perhaps the epitome of this culture of access and encouragement was the founding of the Royal Institution in London in 1799, which was meant to disseminate useful knowledge to the public at large. It was associated with three of the greatest names of the period: Count Rumford was one of its founders, and Humphry Davy and Michael Faraday were among its earliest public lecturers. All three shared the ability to look for laws in nature and think of useful technical applications of what they knew. Davy's most famous invention was the 'miner's friend' (a lamp that reduced the danger of fires in coal mines) but he also wrote a textbook on agricultural chemistry and discovered that a tropical plant named *catechu* was a useful additive to tanning. Rumford, besides his famous refutation of heat being a 'substance', invented a better stove, improved the oil lamp, and made the first drip percolator coffee maker.

Scientific (formal, consensual) knowledge was, however, a small part of what counted. Most of the knowledge on which continued technological expansion rested was far more mundane in nature than the body of knowledge which we think of today when we talk of 'science'. The popular distinction between 'science-based' techniques and 'empirical' techniques refers to the degree of formalisation and generality of the knowledge on which they rest, but this dichotomy seems less than helpful for the economic historian examining the early nineteenth century. Natural regularities may be as 'unscientific' as the cataloguing of trade winds and the apprehension of the rhythmic movements of the tides, which were harnessed for the techniques of transportation and shipping, or the relation between crop rotations and agricultural productivity. The line between 'science' and 'informal useful knowledge' is arbitrary. Our modern notions of 'science' may look as primitive to some future person as pre-Copernican astronomy and pre-Lavoisier chemistry do to us. In the eighteenth century the useful knowledge underlying the new techniques consisted in large part of practical and artisanal knowledge, based on experiments and experience, trial and error, the collection and cataloguing of facts and the search for patterns and regularities in them.[17]

The systematisation and perfection of these methods delivered far more to the industrial revolution than formal science. In this respect, the unsung heroes of the period were the engineers such as John Smeaton, John Rennie and Richard Trevithick. Smeaton's approach was pragmatic and empirical, although he was well versed in theoretical work. He limited himself to ask questions about 'how much' and 'under which conditions' without bothering too much about the 'why'. Yet his approach presupposed an orderliness and regularity in nature exemplifying the scientific mentality. Vincenti (1990: 138–40) and Cardwell (1994: 195) attribute to him the development of the method of parameter variation through experimentation, which is a systematic way of cataloguing what works and how well. By establishing regularities in the relationships between relevant variables, even without knowing why these relationships are true, it can extrapolate outside them to establish optimal performance. It may well be, as Cardwell notes, that this type of progress did not lead to new macroinventions, but the essence of progress is the interplay between 'door-opening' and 'gap-filling' inventions. This work, even

[17] An example of how such incomplete knowledge could lead to a new technique was the much hailed Cort puddling and rolling technique. The technique depended a great deal on prior knowledge about natural phenomena, even if science properly speaking had very little to do with it. Cort realised full-well the importance of turning pig iron into wrought or bar iron by removing what contemporaries thought of as 'plumbago' (a term taken from phlogiston theory and equivalent to a substance we would today call carbon). The problem was to generate enough heat to keep the molten iron liquid and to prevent it from crystallising before all the carbon had been removed. Cort knew that reverberating furnaces using coke generated higher temperatures. He also realised that by rolling the hot metal between grooved rollers, its composition would become more homogeneous. How and why he mapped this prior knowledge into his famous invention is not exactly known, but the fact that so many other ironmasters were following similar tracks indicates that they were all drawing from a common pool. Cort surely was no scientist: Joseph Black famously referred to him as 'a plain Englishman, without Science'.

more than his inventions, stamps Smeaton without question as one of the 'Vital Few' of the industrial revolution.

Pragmatic and experimental knowledge was at the base of many of the key inventions of the classical Industrial Revolution. The great inventions in cotton spinning in the early years of the Industrial Revolution were significant mechanical advances, but it is hard to argue that they depended on any deep scientific insights or even methodology. If they had been all there was to the Industrial Revolution, the scepticism about the role of intellectual factors in economic growth would be well placed. But what needs to be explained is not so much Arkwright's and Crompton's famous 'gadgets' but their continuous improvement beyond their original breakthrough.

To sum up: accounting for the Industrial Revolution involves an understanding of the changes in the culture and technology of useful knowledge that had been in the making since at least the era of Bacon and Galileo. These changes explain the difference between sustained growth and 'just another' episode that would have tapered off to the stationary state that most political economists of the period still expected.

Two further examples will illustrate this argument. One is the career of the engineer Richard Roberts (Hills 2002). Roberts was far from a scientist and never had a scientific education. His invention of the self-actor in 1825 is a famous episode in the history of technology since it was triggered by a strike of mule-operatives. Roberts, however, was a universal mechanical genius with an uncanny ability to access what knowledge was available and turn it into new techniques that worked. His application of the concept of binary coding of information embodied in the Jacquard loom was more immediately useful than the analytical engine of Charles Babbage (which was based on the same principle): he perfected a multiple spindle machine, which used a Jacquard-type control mechanism for the drilling of rivet holes in the wrought iron plates used in the Britannia tubular bridge (Rosenberg and Vincenti 1978). Despite his lack of formal education, he was well networked, elected to the famous Manchester Literary and Philosophical Society in 1823, where he rubbed shoulders with leading natural philosophers such as John Dalton and William Henry. In 1845 he built an electromagnet which won a prize for the most powerful of its kind and was placed in the Peel Park museum in Manchester. When first approached, he responded, characteristically, that he knew nothing of the theory or practice of electromagnetism, but that he would try and find out. By this time, if someone wanted to 'find out' something, one could do so readily by talking to an expert, consulting a host of scientific treatises and periodicals, encyclopaedias and engineering textbooks, as Roberts no doubt did.

The other example is the early applications of chemistry to industry. Most of what chemistry could do for the economy had to await the development of organic chemistry in the 1830s by von Liebig and Wöhler, and the breakthroughs in the fertiliser and dye industries in the second half of the nineteenth century. There were a few famous breakthroughs, of course, such as Leblanc's soda-making process (1787), yet before Lavoisier these all rested on slender or confused chemistry, and without further breakthroughs would have run into diminishing returns.

The insights provided by the new chemistry, coupled to the economic importance of mordants, dyes and soap for the growing textile industry, were such that new work on the topic kept appearing. Among those, the *Art de la teinture* by Claude Berthollet (Lavoisier's most illustrious student) appeared in 1791, not many years after he had shown how chlorine could be turned into an industrial bleaching agent (an idea promptly appropriated by enterprising Britons, among them James Watt, whose father-in-law was a bleacher). Berthollet's book explained dyeing in terms of chemical affinity and summarised the state of the art for a generation. He served as director of dyeing at the *Manufacture des Gobelins*, and his *Statique chimique* (1803) 'was not only the summation of the chemical thought of the entire eighteenth century . . . but also laid out the problems that the nineteenth century was to solve' (Keyser 1990: 237). The knowledge gathered by chemists and manufacturers formed the basis for William Partridge's *A Practical Treatise on the Dyeing of Woollen, Cotton and Silk* that appeared in New York in 1823 and for thirty years remained the standard text 'in which all the most popular dyes were disclosed . . . like cookery recipes' (Garfield 2001: 41). Berthollet's successor at the *Gobelins*, Michel Eugène Chevreul, was interested in lipids, discovered the nature of fatty acids and isolated such substances as cholesterol, glycerol and stearic acid. He discovered that fats are combinations of glycerol and fatty acids, easily separated by saponification (hydrolysis) which immediately improved the manufacture of soap.[18] For some reason, the European continent seemed better at producing advances in chemistry than Britain; this seems to have bothered the British not one iota. They simply sent their chemistry students to study across the channel, or imported the best chemists to teach in Britain. Here as elsewhere during the Industrial Revolution, the advances were pan-European.

In chemicals, much as was the case in mechanical devices, the bulk of the inventions between Berthollet's pathbreaking bleaching process (1785) and the discovery of Aniline Mauve by Perkin in 1856 (which set into motion the synthetic dye industry based on organic chemistry) were relatively small microinventions. However, they rested on ever more chemical knowledge and thus continued to pour forth, instead of slowly petering out. Much of this knowledge was gathered by empirical experimentation

[18] Clow and Clow in their classic account (1952: 126) assess that his work 'placed soap-making on a sure quantitative basis and technics was placed under one of its greatest debts to chemistry'. His better understanding of fatty substances led to the development of stearic candles, which he patented in 1825 together with another French chemist, Gay-Lussac. His work on dyes and the optical nature of colours was also of substantial importance.

rather than based on coherent theory, and thus to some extent a matter of good luck, but clearly the growth of chemical knowledge prepared the fortunate minds of the chemical revolution and thus streamlined the pragmatic and somewhat randomised 'search'.

Thus, for instance, the adoption of early gas lighting was hampered by the ghastly smell caused by sulphur compounds. The pioneers of gas lighting, William Murdoch and Samuel Clegg discovered that the introduction of lime in industrial gas removes the sources of bad odour. Access to the requisite chemical knowledge proved easier than before: Antoine Fourcroy's magisterial *Système des connaissances chimiques* (1800) which codified the new Lavoisier chemistry around the concepts of elements, bases, acids and salts was widely available in Britain. Similarly, the early post-Lavoisier chemistry of Gay-Lussac informed the Scottish ironmaster James Neilson in his invention of the famous hot blast technology which is one of the most pronounced productivity-enhancing invention of the post 1815 era, reducing fuel requirements in blast furnaces by a factor of three. It is hard to see those advances happening in a world without accurate measurement and systematic and informed experimentation. It is perhaps too strong to argue with Clow and Clow (1952: 355) that 'Neilson the scientist succeeded where the practical ironmasters failed' – Neilson had taken some courses in applied chemistry in his twenties, and was a member of the Glasgow Philosophical Society, but he was hardly a 'trained scientist'.

The knowledge revolution meant not only that technological progress could proceed without hitting a conceptual ceiling. The interaction between the two was bi-directional, creating positive feedback. Indeed, some scholars, most notably Derek Price (1984), have argued that the 'loop' going from technology to science was possibly more important than the traditional mechanism in which science informs technology. New instruments and laboratory techniques undoubtedly helped science immensely. Moreover, new techniques whose mode of operation was poorly understood created a 'focusing device' for scientific work by raising the curiosity and possibly financial hopes of scientifically trained people. The most celebrated example of such a loop is the connection between steam power and thermodynamics, exemplified in the well-known tale of Sadi Carnot's early formulation, in 1824, of the Second Law of Thermodynamics by watching the difference in fuel economy between a high pressure (Woolf) steam engine and a low pressure one of the Watt type.[19] Power technology and classical energy physics developed hand-in-hand, culminating in the career of the Scottish physicist and engineer William

[19] It is interesting to note that Carnot's now famous *Reflexions sur la puissance motrice du feu* (1824) was initially ignored in France and eventually found its way second hand and through translation into Britain, where there was considerably more interest in his work because of the growing demand by builders of gigantic steam engines such as William Fairbairn in Manchester and Robert Napier in Glasgow for theoretical insights that would help in making better engines.

Rankine, whose *Manual of the Steam Engine* (1859) made thermodynamics accessible to engineers and led to a host of improvements. In steam power, then, the positive feedback can be clearly traced: the first engines had emerged in the practical world of skilled blacksmiths, mechanics and instrument makers with only a minimum of theoretical understanding. These machines then inspired theorists to come to grips with the natural regularities at work. These insights were in turn fed back to engineers to construct more efficient engines. This kind of mutually reinforcing process can be identified, in a growing number of activities, throughout the nineteenth century.

CONCLUSIONS

Drawing attention to the intellectual sources of the Industrial Revolution does not invalidate any of the traditional economic arguments about the causes of the Industrial Revolution. Relative factor prices and demand played an important role in directing technological progress in particular directions. Incentives to inventors such as the hope of securing a pension or patent royalties motivated ingenious and creative individuals. Secure property rights were essential for continuing investment in the capital goods that embodied the new technology. British institutions did what institutions are supposed to do: they reduced uncertainty. Britain's markets were well developed; its infrastructure was rapidly improving. It provided a healthy environment for would-be entrepreneurs who were willing to take risks and work hard. By 1688 it was already a wealthy and sophisticated country by many standards. Yet in 1700 there still was no way to tell that its wealth and sophistication had the capacity to unleash a force that would change human life on this planet more than anything since the emergence of Christianity. The Industrial Enlightenment increased useful knowledge not only at a rate that was faster than ever before, but at a rate that has been accelerating since.

Britain played a crucial role as spearhead in this movement, and the effects of Britain's leadership on its economy and polity dominated the country until at least 1914. But the *global* significance of the Industrial Revolution is much deeper, since it had the capacity to raise living standards in a wide range of societies. This process had barely taken off by the time the Industrial Revolution was over, but by 1914 it was unmistakable. The full implications of this event are still as mind-boggling today as they were in 1776.