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Understanding Productivity Growth in the Industrial Revolution

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Abstract

Recent research relating to productivity growth during the British industrial revolution is reviewed. This confirms that there was a gradual acceleration rather than a 'take-off'. The explanation for the speeding-up of technological progress remains controversial but the evidence base has improved considerably. In the face of a surge in population growth, slow growth of real wages during the industrial revolution may be seen as a good outcome which was underpinned by improved growth potential. Slow total factor productivity growth from the 1870s suggests that British technological capabilities at the end of the industrial revolution were still quite limited.

Keywords: climacteric; enlightenment; high-wage economy; industrial revolution; labour share; real earnings; TFP growth

JEL Classification: N13; O47.

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1. Introduction.

The British industrial revolution was a landmark event in world economic history. While it was once seen as a period of dramatic 'take-off', it is now generally accepted that it was an episode of gradual acceleration in labour productivity growth which eventually led to sustained increases in living standards. Even so, the unprecedented transition to modern economic growth which it entailed rightly continues to attract massive amounts of research effort and literature has evolved rapidly in recent years.

Despite a considerable increase in the sophistication of analysis, important (and exciting) questions remain controversial. These include 'why did productivity growth accelerate?', 'how soon did workers benefit from faster productivity growth?', and 'why did productivity growth experience a major slowdown as soon as the 1870s?' Much progress has, however, been made and now is an opportune moment to take stock. In this paper, I will do so from a macroeconomic vantage point informed by ideas from growth economics as well as economic history. This will necessarily be a somewhat selective survey given the volume of research that has been produced in which I have opted for treatment of a few aspects in depth rather covering a wide terrain superficially.

I begin by setting out estimates of productivity growth derived from recent research and exploring them in a growth accounting framework. Given that the estimates of total factor productivity growth in this period are underwhelming, I follow up by explaining why this is a plausible finding even though there were many famous inventions. I also explore the revised picture of sectoral growth rates that has emerged from recent research. I then review competing explanations for the move to faster productivity growth during the industrial revolution and the evidence for them. I also look at the relationship between productivity growth and real wage growth to develop some new insights into the standard of living debate. Finally, I consider why productivity growth soon declined from the rate achieved in the mid-nineteenth century at the end of the industrial revolution.

My main conclusions are as follows. First, improved estimates of labour quality and hours worked reinforce the conclusions of the revisionist literature of the 1980s that total factor productivity growth during the industrial revolution was modest at least until the second quarter of the nineteenth century. Second, viewing labour productivity in terms of real GDP per hour worked highlights that there was a marked slowdown in productivity growth from the 1870s. This suggests that viewing the 'climacteric' as a post-1899 blip is seriously mistaken. Third, there has been much research on the hypotheses that improved productivity growth at the time of the industrial revolution was due to a 'high-wage' or an 'enlightened' economy. Neither is a fully persuasive hypothesis but viewing the industrial revolution through the lens of induced innovation in an economy with a responsive supply-side is attractive. Fourth, the pessimistic view of the impact of the industrial revolution on living standards fashionable in the last twenty years has gone too far. Slow real wage growth was a good outcome in the face of huge demographic pressure.

2. Growth Accounting Estimates

Growth accounting is a useful way to describe the proximate sources of economic growth.[1] These are the growth of factor inputs (capital, labour and land) weighted according to their importance in production and a residual contribution from total factor productivity (TFP) growth. The latter is often thought to represent the contribution of technological change but in practice will also reflect changes in efficiency and scale economies. If the industrial revolution is conceived as a great leap forward in

[1] For a detailed discussion of various refinements to and limitations of this technique as used in economic history, see Crafts and Woltjer, 'Growth accounting.'

technology with an economy-wide impact, then it might be expected that TFP growth would be very rapid, perhaps on a par with the rate achieved by the United States around the mid-20th century.[2] The would perhaps be the prior of T.S. Ashton's famous (notorious?) schoolboy.[3]

The conventional growth accounting formula is

$$\Delta Y/Y = s_K \Delta K/K + s_L \Delta L/L + s_N \Delta N/N + \Delta A/A \quad (1)$$

where Y is real GDP, K is capital, L is labour, N is land and $\Delta A/A$ is the rate of total factor productivity growth which is obtained as a residual that balances the equation while s_K, s_L, and s_N are the factor shares of capital, labour and land, respectively. This is the so-called 'primal formula' for the sources of growth but an equivalent so-called 'dual formula' can be derived as follows.

The national income identity is

$$Y = \pi K + wL + rN \quad (2)$$

where K is capital, π is the rate of profit, L is labour, w is the wage rate, N is land and r is the land rental rate. So, taking logarithms and differentiating with respect to time

$$\Delta Y/Y = s_K(\Delta\pi/\pi + \Delta K/K) + s_L(\Delta w/w + \Delta L/L) + s_N(\Delta r/r + \Delta N/N) \quad (3)$$

Rearranging (3) gives

$$\Delta Y/Y - s_K \Delta K/K - s_L \Delta L/L - s_N \Delta N/N = s_K \Delta\pi/\pi + s_L \Delta w/w + s_N \Delta r/r \quad (4)$$

The left hand side of equation (4) is the primal formula for TFP growth which is the rate of output growth minus the rate of growth of total factor inputs while the right hand side is the dual formula for TFP growth which is the sum of the factor-share-weighted factor rewards.

Feinstein was an early exponent of growth accounting based on the primal formula in the context of the British industrial revolution. An adapted version of his estimates is reported in Table 1.[4] Also reported in that table are estimates based on the Crafts-Harley view of the industrial revolution. The main difference between them is that the latter found much lower growth of TFP in the 1800 to 1830 period compared with Feinstein. In turn, that mainly reflected a lower estimate of growth of real GDP based on a major revision of the earlier estimates made by Deane and Cole which Feinstein had used.[5]

Recently, the Crafts-Harley estimates of real GDP growth have been superseded by those made by Broadberry et al.[6] estimates built up from the output side. Their work entails construction of new indices of real output for the agricultural, industrial and services sectors which extend the coverage and improve the weighting of earlier estimates. Sectoral value-added weights are then used to obtain annual estimates of real GDP which had not previously been available. Broadberry et al. confirm that the earlier study by Deane and Cole (1962), which deflated estimates of nominal income for benchmark years by an inappropriate price index, significantly overestimated output growth during the early 19th century. In fact, the new estimates suggest that growth in the first three decades of the century was even a bit slower than estimated by Crafts and Harley.

[2] According to the estimates in Bakker et al., 'Sources of growth', Table 3, American TFP growth peaked at 2.2 per cent per year in 1960-73.
[3] According to Ashton, *Industrial revolution*, p. 48, this schoolboy said that 'a wave of gadgets swept over England'.
[4] Feinstein, 'Capital accumulation.' The dual formula was first employed by Antras and Voth, 'Factor prices.'
[5] Deane and Cole, *British economic growth*.
[6] Broadberry et al., *British economic growth*.

The new output growth series in Broadberry et al. is the basis for the primal growth accounting estimates reported in Table 2. These also incorporate updated factor shares. The picture that they present is more like Crafts and Harley than Feinstein but for 1800 to 1860 gives somewhat slower TFP growth than those earlier estimates. It is helpful also to examine TFP growth estimates based on the dual method which with perfect data should arrive at the same figure. In practice, there is some discrepancy between the primal and the dual estimates which are a bit higher. Nevertheless, they confirm a picture of initially rather slow TFP growth which accelerated as the industrial revolution matured.

Three key points can be taken from Table 2. First, modest TFP growth was a major reason for underwhelming labour productivity growth before 1830. Second, as the dual formula in equation (4) makes clear, TFP growth is what is available for increases in the returns to factors of production – if TFP growth was slow, real wage rates were unlikely to rise rapidly. Third, especially given its large factor-share weight, slow real wage growth underpins the plausibility of an estimate of modest TFP growth.

At first sight, the growth-accounting estimates in Table 2 may seem to undermine McCloskey's well-known claim that 'ingenuity rather than abstention governed the industrial revolution' (1981, p. 108) which was made at a time when Deane and Cole's estimates of economic growth during the Industrial Revolution were the conventional wisdom. Table 2 reports that TFP growth contributed only about 25-33 per cent of output growth during 1770-1860. However, if, as is more appropriate, the focus is on the sources of labour productivity growth, then McCloskey was right and TFP growth rather than physical-capital deepening accounted for the lion's share – more than 80 per cent - of labour productivity growth.[7]

Most growth accounting estimates do not include a component for the contribution of the growth of land inputs but prefer to let it be included in the residual. On the other hand, it is usual to take account of labour quality (or human capital) and is often quite informative to present the accounts in terms of labour productivity. If labour quality is not treated separately, the relevant (primal) formula is as follows.

$$\Delta(Y/L)/(Y/L) = s_k\Delta(K/L)/(K/L) + \Delta A/A \qquad (5)$$

If a contribution from labour quality growth is distinguished, then the formula becomes the following:

$$\Delta(Y/L)/(Y/L) = s_k\Delta(K/L)/(K/L) + s_L\Delta(LQ/L) + \Delta A/A \qquad (6)$$

where LQ is an index of labour quality.

Growth accounting estimates in the 1980s were based on measuring labour inputs in terms of workers but, where possible, it is preferable to use hours worked. There are two reasons why it is important to consider what productivity growth looks like using the best available estimates of hours worked. First, at least for the early decades of the industrial revolution it is generally thought that hours worked per year were increasing so that estimates on a per-worker basis exaggerate labour productivity growth. Second, in order to get an appropriate perspective on the productivity slowdown which came after the industrial revolution estimates on an hours-worked basis are essential because of significant changes in the work week in the 1860s and 1870s.

[7] Labour productivity growth is the rate of GDP growth minus the rate of labour force growth which is (0.2 + 0.3 + 1.2)/3 = 0.57. Primal TFP growth is the lower of the two and averages (0.26 + 0.38 + 0.76)/3 = 0.47. TFP growth accounts for 0.47/0.57 = 82 per cent of labour productivity growth.

For hours worked during the industrial-revolution period the best option appears to be the series derived from the work of Humphries and Weisdorf.[8] This is based on a massive compilation of wage rates from historical sources with days worked inferred by assuming that annual earnings of day-wage workers and those on annual contracts were the same. It is perhaps fair to say that pre-1856 estimates of hours worked should be regarded as not very reliable.[9] In any case, the adjustments to the growth of labour inputs are quite modest in this period. For 1856-1913, Thomas and Dimsdale include a series for hours worked which uses various additional sources to implement on an annual basis the basic methodology which Matthews et al. used to make estimates for a few benchmark years; this permits a new view of labour productivity during the so-called climacteric.[10] This series is continued for later years using the standard official sources of the *Ministry of Labour Gazette* and then the *Labour Force Survey*.

Table 3 reverts to more conventional growth accounting based on equations (5) and (6) with the periodization designed to mesh with the classic work of Matthews et al. and its spin-off, Feinstein et al., on the post-1856 period.[11] In the first part of the table, there are two main points to note. First, the omission of an explicit growth contribution from land inputs combined with a somewhat larger factor share for capital lowers estimated TFP growth while leaving the same basic pattern of rather belated acceleration to a peak in the third quarter of the nineteenth century. Second, there is a marked drop in both labour productivity growth and TFP growth after 1873. Indeed, the major fall in labour productivity growth occurs after 1873 (rather than after 1899) in the new estimates, from 2.06 per cent in 1856-1873 to 1.18 per cent per year in 1873-1899 and 0.84 per cent per year from 1899 to 1913 which compares with 1.3 to 1.2 to 0.5 per cent per year, respectively, in Feinstein et al..[12] This is almost entirely because they examined the climacteric in terms of output per worker rather than output per hour worked.[13] The so-called 'climacteric' belongs in the 1870s as an earlier historiography believed.[14]

A significant weakness of the Thomas and Dimsdale dataset for growth accounting is that it does not contain estimates of labour quality which can be used to augment hours worked in arriving at labour input. Using crude estimates of relative earnings to weight different types of labour, Matthews et al. made estimates for benchmark years although they regarded their results with some caution. Nevertheless, their estimates, which include contributions from changes in the composition of the labour force as well as schooling, are still the best available for the years 1856 to 1913.[15] Prior to that

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[8] Humphries and Weisdorf, 'Unreal wages' as reported in Thomas and Dimsdale, 'Millennium', Table A54, column F. Days worked per year rise from 297.4 in 1760 to a peak of 341.3 in 1817 before slowly declining.

[9] Feinstein, 'Pessimism perpetuated.' Alternative estimates for benchmark years in Voth, 'The longest years', show a considerable rise in hours worked between 1760 and 1800 and would imply negative labour productivity growth in that period.

[10] Thomas and Dimsdale, 'Millennium', Table A54, column AW. The starting point is estimates of average fulltime weekly hours worked with allowances then made for overtime, short-time and part-time working. Adjustments are then made to allow for holidays, sickness and strikes. The method is explained in more detail by Matthews et al., *British economic growth* in their Appendix D with sources listed in Table D1.

[11] Matthews et al., *British economic growth*; Feinstein et al., "The timing." The table is entirely derived from the Thomas and Dimsdale, 'Millennium' and is based on the most recent output growth estimates.

[12] Feinstein et al., 'The timing.'

[13] This was done apparently because they only made estimates for hours worked for the benchmark years of 1856, 1873 and 1913 and so could only discuss sub-periods within 1873-1913 in terms of employment. However, a reader of Matthews et al., *British economic growth*, whose estimates were based on output per hour worked, would have thought that productivity growth fell sharply after 1873.

[14] Crafts and Mills, 'Sooner than you think.'

[15] Matthews et al., *British economic growth*.

date, recent research by de Pleijt has provided estimates of years of schooling using evidence on literacy rates and on the number of secondary schools to calculate primary- and secondary-school years, respectively. These can be used as the basis for an (incomplete) index of labour quality using the same assumption as Matthews et al. about the return to educational attainment.[16]

Taking account of labour quality based on years of schooling makes virtually no difference during the industrial revolution, as Table 3 shows. Taken at face value, on this basis the contribution of labour quality to productivity growth was negligible. On the other hand, taking account of labour quality in the late nineteenth century makes slow TFP growth at that time a serious issue.

A better index of labour quality during the industrial revolution is obviously desirable but there are reasons to believe that there was little growth in skills per worker. Williamson made an estimate of the growth of skills per worker based on a weighted average of wage premia for various occupations. His preferred estimate showed growth rates of 0.06 per cent per year for 1821 to 1861 then increasing to 0.69 per cent per year for 1861 to 1911.[17] De Pleijt and Weisdorf analysed parish register data on occupations using a skill classification approach and found that the share of unskilled workers was increasing over time from about 30 per cent in 1700-49 to 33 per cent in 1750 to 1799 and about 40 per cent in 1800 to 1849.[18]

It is important, however, to recognise that skills matter for TFP growth and this effect is not captured by measurement of the contribution of labour quality as a direct input to output growth. In this context, the key role may have been played by a small fraction of the labour force, engineers, mechanics, millwrights etc. who were central to the diffusion and incremental improvement of new technologies.[19] The supply of these skills was founded on an effective and responsive apprenticeship system through which a significant proportion of inventors had been trained.[20] Unfortunately, it is not possible to quantify the impact of the availability of skills on the rate of TFP growth.

3. Is Slow TFP Growth Plausible?

The Industrial Revolution was a time of famous inventions including those of Richard Arkwright, Henry Cort, Samuel Crompton, George Stephenson, and James Watt. Watt invented the (improved) steam engine, thus inaugurating what is generally thought to be one of the most important general-purpose technologies ever. Prima facie, this 'wave of invention' seems to suggest that TFP growth would speed up dramatically. So, is the TFP growth rate found by growth accounting plausible?

An interesting challenge to this finding was made by Sullivan. He argued that it was at odds with the statistics on patenting which showed a break of trend at 1757. Before that date the number of patents grew at 0.54 per cent but then accelerated to 3.63 per cent per year.[21] This analysis, however made no allowance of the quality of patents which has subsequently been measured by Nuvolari and Tartari on a quasi-citation basis. They find that a significant number of patents representing technological breakthroughs are found in the later eighteenth century but that the proliferation of lower-quality patents which were the microinventions that realized the productivity potential of these ideas came

[16] De Pliejt, 'Human capital.' This entails assuming a 6 per cent increase in labour quality per year of schooling. Years of schooling were 1.36 in 1700 and 1.43 in 1830 before rising to 2.05 in 1856.
[17] Williamson, *Did capitalism*, p. 237.
[18] De Pliejt and Weisdorf, 'Human capital.'
[19] Meisenzahl and Mokyr, 'Rate and direction.'
[20] Khan, 'Human capital.'
[21] Sullivan, 'England's age of invention.'

after about 1820.[22] As these authors say, this pattern is what might be expected in light of the growth accounting estimates.

The process of technological advance was characterized by many incremental improvements and learning from experience to improve upon the original inventions. This took time in an era where scientific and technological capabilities were still quite weak by later standards. Steam power offers an excellent example. The growth accounting estimates in Table 4 show that its impact on productivity growth before 1830 was trivial – as was made clear many years ago by the detailed quantitative research of von Tunzelmann and Kanefsky.[23] In 1830, only about 165,000 horsepower were in use. The cost effectiveness and diffusion of steam power was held back by the high coal consumption of the original low-pressure engines and the move to high pressure – which benefited not only factories but railways and steam ships - was not generally accomplished until the second half of the 19th century. The science of the steam engine was not well understood and the price of steam power fell very slowly compared with that of computers in modern times, especially before about 1850. The maximum impact of steam power on British productivity growth was delayed until the third quarter of the 19th century – nearly 100 years after James Watt's patent. This is a classic example of a general-purpose technology which had a large impact on productivity but only after a long lag.[24]

Even if TFP growth at the whole economy level was steady rather than spectacular, this does not preclude rapid TFP growth in some 'modernized' sectors, as is reported in Table 5. Indeed, an obvious point to make is that technological progress during the industrial revolution was very uneven across the economy and sectors where technological advance was negligible loomed quite large. In 1851, 24.3 per cent of the labour force was employed in the 'services and professions' or 'dealers and sellers' categories compared with 8.8 per cent in textiles and 2.8 per cent in iron and steel.[25]

Table 5 shows that relative to the primal estimate of overall TFP growth about two-thirds of TFP growth (0.334/0.51) originated in the four named sectors. This does not mean, however, TFP growth was very slow or, indeed, absent apart from these sectors. For example, an industry in which rapid TFP growth has been quantified is watchmaking where real prices fell by 1.3 per cent per year between 1709 and 1810.[26] TFP growth estimates at the level of the individual sector are, however, not generally available. Of course, most industries were small enough that even rapid TFP growth would make little impact on the macroeconomy and could be buried inside the contribution of the 'rest' in Table 5.[27] As Mokyr put it, 'there were too many [other industries experiencing technological progress] to sustain arguments that the industrial revolution was confined to so few industries that it was negligible, but too few to have major macroeconomic effects before 1830.'[28]

4. Labour Productivity Growth in Agriculture and Industry

The aspect of the estimates that I made in my 1985 book which was hardest to swallow was the finding that labour productivity growth exceeded that in industry by a large margin. This was heavily criticized even by writers who accepted that productivity growth for the whole economy was considerably lower

[22] Nuvolari and Tartari, 'Bennet Woodcroft.'
[23] Kanefsky, 'Diffusion'; von Tunzelmann, *Steam power*.
[24] Crafts, 'Steam.'
[25] Shaw-Taylor and Wrigley, 'Occupational structure.'
[26] Kelly and O'Grada, 'Adam Smith.'
[27] If the dual estimate of TFP growth is adopted, obviously these leaves more scope for a few other sectors to have experienced rapid TFP growth, as Table 5 makes clear.
[28] Mokyr, *Enlightened economy*, p. 137. He lists copper, bleaching, ceramics, gas lighting, cement, papermaking, and machine tools as activities in which technology advanced.

than had previously been believed.[29] The revisions to output and labour force growth made by Broadberry et al. restore the traditional picture of faster productivity in industry.[30]

Partly this is because sectoral output growth rates have changed as can be seen in Table 7 but the more important reason is that estimates of the shares of the labour force in agriculture and industry in 1759 and 1801 have been significantly revised, as can be seen in Table 6. The new estimates which derive from a careful re-working of the social tables constructed by Massie and Colquhoun were informed by research by Shaw-Taylor and entail a substantial improvement in the treatment of female employment. This is instrumental in the finding that the labour force was considerably more industrialized prior to the industrial revolution than had been thought.[31]

The reduction in agriculture's share from 48.0 to 36.8 per cent of employment in 1759 together with the increase in industry's share from 23.8 to 33.9 per cent combined with relatively small changes to the shares in 1851 implies much faster growth of the labour force in agriculture and much lower growth of industrial employment during the industrial revolution than was previously believed. This is a major change, in particular, because of the implications for the locus of productivity growth during the industrial revolution which can be seen in Table 7.[32] In Broadberry et al.'s estimates, industrial labour productivity growth is higher than that in agriculture throughout, and by a large margin, thus removing Crafts's anomalous finding that the opposite was the case.

Broadberry et al. say that their findings "reconcile the output estimates of Crafts and Harley with traditional views of an industrially dynamic industrial revolution" and state that "The once orthodox view that industry was indeed the most dynamic sector during the classic Industrial Revolution is thus reinstated, along with the idea that mechanization based upon technological advance delivered sustained productivity gains to Britain's slowly expanding industrial labour force."[33] This is fair enough in terms of the general historiography of the industrial revolution with regard to relative sectoral contributions to productivity growth but nevertheless can mislead the unwary reader.

Those who absorb the rhetoric without fully appreciating the numbers, might think that these new results can rehabilitate a conventional 1960s' view of the industrial revolution. As is clear from the comparison of different vintages of estimates in Table 7, this is quite wrong. It is worth noting that Deane and Cole did not believe that productivity growth was dominated by industry but, more importantly, the picture emerging from the Broadberry et al. estimates is hardly a return to the so-called 'traditional view' of the industrial revolution. The picture of slower growth of output both in the economy overall and in industry compared with Deane and Cole that was presented by Crafts and Harley is endorsed. Similarly, the new estimates of overall labour productivity growth are a little higher than those of Crafts and Harley but are nowhere near to restoring Deane and Cole's story.

5. Why Did Productivity Growth Accelerate?

Productivity growth accelerated during the industrial revolution. Obviously, to explain this it is necessary to go beyond the proximate sources of growth considered above. There is, of course, a

[29] See for example, De Long, 'Review' and Williamson, 'Debating.'
[30] Broadberry et al., *British economic growth*.
[31] Shaw-Taylor, 'Occupational structure.'
[32] It should be recognised that the structure of employment c. 1760 is still controversial and estimates must be treated with caution. Wallis et al., 'Structural change', based on probate records estimate for 1740-1759 a share for industry slightly lower than Broadberry et al. but put agriculture at roughly the same as the estimate made by Crafts. The most recent estimate from the Cambridge Group reported in Shaw-Taylor et al., 'Preliminary estimate', is that industry's share in 1761 was 48.8 per cent with services only 17.1 per cent.
[33] Broadberry et al., 'When did Britain', p.17 and p.26.

massive historiography on this topic which continues to grow relentlessly. In this section, I do not attempt to survey this literature. Rather, I undertake a more manageable task, namely, to review developments in the controversy provoked by the high-profile and competing explanations of the Industrial Revolution published by Allen and Mokyr in 2009.[34] In what follows, I concentrate on developments since I wrote a review essay on this topic published in 2011.[35]

Mokyr conceptualizes the industrial revolution as "the set of events that placed technology in the position of the main engine of economic change".[36] His aim is to explain this phenomenon. He sums up his thesis as follows: "Britain became the leader of the industrial revolution because, more than any other European economy, it was able to take advantage of its endowment of human and physical resources thanks to the great synergy of the Enlightenment: the combination of the Baconian program in useful knowledge and the recognition that better institutions created better incentives."[37] Mokyr argues that what was needed to generate an industrial revolution was the right combination of useful knowledge generated by scientists, engineers and inventors to be exploited by a supply of skilled craftsmen in an institutional environment that produced the correct incentives for entrepreneurs. The industrial revolution is seen as the invention of a new method of invention based on systematic empiricism and experimentation that established what worked and which accumulated and made accessible useful knowledge which could promote sustained technological advance.

This interpretation fits naturally into the basic model of endogenous growth outlined by Carlin and Soskice which is represented in Figure 1.[38] Here the equilibrium rate of technological progress is determined by the intersection of the Schumpeter and Solow lines.[39] The former can be written as:

$$X = \lambda\sigma q \quad (7)$$

where the rate of technological progress, x, depends on the amount of innovative effort or research intensity, q, the probability of successful innovation per unit of effort, λ, and the extent to which each innovation raises productivity, σ. Innovative effort increases with market size, inter alia, hence the upward slope of the Schumpeter line.

The implications of the new method of invention of the industrial revolution were to increase each of the variables on the right-hand side of (7). The probability of successful innovation was raised by the availability and accessibility of more knowledge, this encouraged more innovative effort since expected returns increased and the impact of innovations was enhanced by a greater capability of improving initial designs and through more effective diffusion of new technology.

Evidence to provide support for these arguments has grown since Mokyr's book appeared. One important study examined the role of 'knowledge access institutions' (KAIs) which might be regarded as central to the accumulation and diffusion of an evidence-based method of invention. KAIs were organizations whose objectives were to produce and disseminate scientific and technological knowledge, of which the first was the Royal Society (1660) and which included the Lunar Society (1765), the Manchester Literary and Philosophical Society (1781), the British Association for the Advancement of Science (1831) and Mechanics Institutes from 1823. The total number of Core KAIs was only 3 in 1761 but had risen to 60 by 1801 and 1014 by 1851 of which 800 were Mechanics

[34] Allen, *British industrial revolution*; Mokyr *Enlightened economy*.
[35] Crafts, 'Explaining.'
[36] Mokyr, *Enlightened economy*, p.5.
[37] Ibid., p.122. In 'Explaining' I reviewed the claim that the Enlightenment was good for the institutional environment and concluded that the glass was probably not even half-full.
[38] Carlin and Soskice, *Macroeconomics*.
[39] See appendix 1 for further explanation of the diagram.

Institutes. Core KAIs had a strong causal impact both on total patenting and on high-quality patenting in their localities.[40]

Micro-invention is at the heart of technological advance according to Mokyr, especially in terms of realizing its productivity potential. If the Industrial Enlightenment hypothesis is to be fully persuasive, it is important to show that there was a substantial impact on micro-invention. Meisenzahl and Mokyr have made some progress on this issue by analysing the biographical information available on tweakers and implementers, which is summarized in Table 8. In their sample, they describe 52 per cent of these people as being 'enlightened' in the sense that they published, were members of a professional society or both.[41] It is striking, however, that of the subset from the textiles sector only 9 per cent were in this category and 80 per cent have no record of being educated.

The tweakers and implementers are an elite group, however, and the Mokyr hypothesis would be more convincing if it can also be shown that artisans, craftsmen and mechanics in general were affected by the Enlightenment. The proliferation of Mechanics Institutes may suggest this. A further important component was the spread of skills in applied mathematics which underpinned measurement and calculation.[42] Here a key implication was the development of machine tools that were required to convert inventions into working machinery.

Whereas Mokyr stresses the capability to develop new technology, Allen focuses on the incentive to do so. His explanation for the time and place of the first industrial revolution can be summarized as follows. His conclusion is deceptively simple: "The Industrial Revolution, in short, was invented in Britain in the eighteenth century because it paid to invent it there."[43]

This interpretation is reached in several steps. First, it is stressed that "Britain's unique price and wage structure was the pivot around which the industrial revolution turned."[44] International comparisons show Britain had relatively high wages but cheap capital and very cheap energy. Second, Allen points to the high fixed costs of developing 'macro-inventions' into commercially viable technologies through research and development; he argues that these will only be incurred where the technology is profitable to adopt, a decision which turns on relative factor prices, and where the market is big enough that success in perfecting the technology will deliver enough sales to reward the proprietor.[45] Third, the profitability of adopting several inventions including the spinning jenny, Arkwright's mill, and coke smelting is examined with the result in each case that adoption (and therefore invention) is rational at British but not at French prices.[46]

So, for example, the rationality of adoption of the spinning jenny is evaluated in terms of the internal rate of return which is derived from the expression

$$J = \Sigma(w\Delta L - m)/(1 + r)^t \quad (8)$$

where J is the price of the jenny, w is the daily wage of a spinner, m is the additional maintenance cost of the jenny assumed to be 10% of the purchase price each year and the lifetime of the machine is 10 years. ΔL is the saving of labour based on the formula

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[40] Dowey, 'Mind over matter.' Dowey recognises that there is a problem of potential endogeneity of KAIs and uses an instrumental-variable approach relying on early evidence of rational dissent as an instrument.

[41] Meisenzahl and Mokyr, 'Rate and direction.'

[42] Kelly and O'Grada, 'Connecting.'

[43] Allen, *British industrial revolution*, p.2.

[44] Ibid., p.15.

[45] Ibid., pp. 141-2, 151-4.

[46] Ibid., ch.8-9.

$$\Delta L = YD(1 - 1/P) \qquad (9)$$

where Y is the number of days the jenny is used each year, D is the proportion of a full day that it was used for, and P is the relative labour productivity of a spinner with the jenny compared with the spinning wheel.

The idea of induced innovation has become respectable among economists during the last twenty years or so as models which embody firm foundations in microeconomic theory have been developed. The model set out by Acemoglu predicts the direction of technical change in a setting where innovative effort responds to market signals.[47] In this model, both relative-price and market-size effects matter. The importance of the market size effect can be understood in terms of expected profitability in the context of incurring fixed costs in development of a new technology. Thus, Allen's analysis is theoretically defensible and his emphasis on the costs of development of a technology goes with the flow of recent growth economics. In the spirit of Acemoglu's model, the decision to incur the development costs for the technologies that were central to the industrial revolution would be predicted to depend on the number of potential adopters. In turn, this would depend both on whether it was profitable for firms to adopt the technology, given factor prices, and on market size.

Recently, evidence pointing to the importance of economic incentives for invention has been provided in a paper which examined probated wealth over the period 1800 to 1870 in Meisenzahl and Mokyr's sample of inventors and compared it with the male population in 1858.[48] Bottomley found that 61.4 per cent of inventors left more than £1,000 compared with 5.6 per cent of all males while 36.7 per cent of inventors left more than £10,000, in other words, 'invention paid.'[49]

Moreover, a recent study of patenting found that a relatively high proportion of 'top-quality' patents (38 per cent in 1700-1799) were labour saving with many of them for machinery.[50] However, this paper was not able to show that high wages motivated these inventions. Nuvolari et al. also noted that the most important of the machinery patents were granted to professional engineers and millwrights which underlines that responding to an incentive to save labour required the right sort of human capital.

Allen's hypothesis about British primacy in the industrial revolution and the acceleration of productivity growth that came with it relies upon real wages being high by international standards. This has been strongly challenged on two quite separate grounds. First, Kelly et al. suggest that what would really matter to an employer is not wages per se but unit labour costs, i.e., wages adjusted for labour productivity. They argue that better nutrition meant that British workers were stronger and had higher cognitive ability than French workers and presumably, those in most other countries. These advantages meant that employing British workers was not unusually expensive.[51] This point is correct in principle but the importance of this in different activities is unclear.[52] Second, Stephenson shows that statements apparently of the wages paid to building workers in London include mark-ups typically in the range 20 to 30 per cent which accrued to contractors.[53] This could mean that wages in

[47] Acemoglu, 'Directed technical change.'
[48] Bottomley, 'Returns.'
[49] Ibid, p.514.
[50] Nuvolari et al., 'Patterns of innovation.'
[51] Kelly et al., 'Precocious Albion.'
[52] They provide evidence (ibid., Table 1) that labour productivity in threshing was about 65-75 per cent higher in England than in France but this is presumably not typical of all economic activity.
[53] Stephenson, '"Real" wages?'

London were actually no higher than in Amsterdam, Antwerp or Paris.[54] This inference turns not only on interpretation of the British sources but also on understanding the intricacies of payments to workers in foreign cities and has been strongly contested by Allen.[55] At this stage, perhaps the jury is still out.

The most discussed of Allen's specific examples of the role of the wage and price configuration for the rational adoption of the technology in Britain but not in France is that of the spinning jenny invented by Hargreaves in 1764. Allen calculated a rate of return for Britain of 38 per cent compared with 2.5 per cent for France – well below the 15 percent that he regarded as a minimum requirement.[56] This estimate does not seem justified by the available evidence on wages and prices and, moreover, does not take account of the differences between the structure and output mix of the cotton textile industries in Lancashire and Normandy (see Appendix 2).

The spinning jenny does not represent 'the industrial revolution in miniature' as in the big picture painted by Allen.[57] However, it does seem appropriate to regard Hargreaves's invention as a response to the challenge of rising costs faced by the Lancashire industry in the 1750s and 1760s.[58] Textiles may still turn out to epitomize induced innovation, although not quite as suggested by Allen, especially since in the early stages of the industrial revolution it appears to be a sector where inventions cannot easily be connected to the Industrial Enlightenment.

It is also quite striking that Acemoglu himself has a very different idea as to how an induced innovation story might play out for Britain in the industrial revolution. He notes that market-size effects can be expected normally to dominate relative-price effects and argues that the key influence on technical progress may have been the very rapid growth in the supply of unskilled labour in the early decades of the Industrial Revolution.[59] Yet, this presumably had a negative impact on the growth of real wages and was, if anything, undermining the high-wage economy. This is no more than a hypothesis but one which may deserve further investigation.

Neither the Allen nor the Mokyr explanations for faster technological progress at the time of the industrial revolution appears fully satisfactory. If the economic environment was unusually conducive to invention, there is much more work to do to spell out the details beyond the original appeal to high wages and cheap energy while the unimportance of the Enlightenment for the breakthroughs in textiles means a significant fraction of TFP growth (cf. Table 5) is not explained by the Baconian program. The Allen and Mokyr approaches are not mutually exclusive, however, and it may be that some combination of the two will emerge in due course along the lines that expected profits mattered to inventors but the ability to respond effectively to potentially profitable opportunities depended upon technical competence and access to useful knowledge.

A step in this direction of bringing together the insights of the two traditions may be to return to the fundamental point that the incentive to develop new technologies to the stage where they are commercially viable depends crucially on the expected number of adopters. This entails absorptive capacity based on the technical skills of the labour force as well as costs and market size. In this context, it is worth noting that counties in which textile employment was concentrated in 1831 were areas in which there were relatively high number of mechanics and toolmakers in the late eighteenth

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54 Stephenson, 'Mistaken wages.'
55 Allen, 'Real wages once more.'
56 Allen, *British industrial revolution*, p.194.
57 Allen, 'Industrial revolution.'
58 Styles, 'Rise and fall.'
59 Acemoglu, 'Directed technical change.'

century.[60] Moreover, the supply of apprentices was highly responsive to textile inventions.[61] If the direction of technological change was perhaps influenced by an ample supply of unskilled labour its implementation required skills whose availability underpinned the diffusion of innovations.

6. What Does Slow Growth of Real Wages Tell Us?

An important facet of productivity growth during the industrial revolution is its relationship with the growth of real wages which are, of course, a central aspect of the standard of living debate. The slow growth of real consumption earnings during the industrial revolution is often seen as a very disappointing outcome. Feinstein himself concluded that it was almost a century before the majority of the working class obtained any economic benefits from the industrial revolution.[62] The failure of real wages to increase significantly during the classic industrial revolution period and, linked to this, an inference that capitalists rather than workers reaped the rewards of productivity growth was highlighted by Allen in a well-known paper as 'Engels' pause'.[63]

However, if real wages and real GDP per worker growth are to be compared, it is important to use appropriate price deflation of the nominal series which has only recently become possible. Labour's share of national income (LS) can be defined as $wL/pY = (w/p)/(Y/L)$ where w is money wages, p is the GDP deflator, L is labour input and Y is real GDP. Given an estimate of the share of labour in a base year, the share in other years can be calculated using the ratio of real product wages divided by base year real wages to GDP per worker divided by base year GDP per worker in each case using the GDP deflator to estimate the real values, i.e.

$$LS_t = LS_0[(w/p)_t/(w/p)_0]/[(Y/L)_t]/(Y/L)_0] \qquad (10)$$

If real product wages grow at the same rate as real GDP per worker, labour's share in national income will remain unchanged. That is what happened in the long run between 1770 and 1830, as is implied by the estimates in Table 9 which are derived using the well-known estimates of annual earnings made by Feinstein.[64] On the basis of these growth rates, in 1830, real GDP per worker was 124.7 and real product wages were 124.3 (1770 = 100). The factor-share estimates in Table 8 show that labour's share in 1830 was marginally lower than in 1770.

Over the long run, Table 10 suggests that there is no reason to think that technological progress or productivity growth came at the expense of labour's share of national income. In that respect, the notion of 'Engels' pause' as put forward by Allen seems to be unacceptable given the data now available.[65] However, real consumption earnings, which are money earnings deflated by a cost-of living index, did grow more slowly between 1770 and 1830, as is reported in Table 9. They lagged behind real GDP per worker and only reached 114.3 in 1830.[66]

Putting these estimates together would suggest that the cost of living increased by more than the GDP deflator. This is indeed the case: in 1830, Allen's cost of living index stood at 146.1 (1770 = 100)

[60] Kelly et al., 'Mechanics.'

[61] Feldman and van der Beek, 'Skill choice.'

[62] Feinstein, 'Pessimism Perpetuated', p. 652.

[63] Allen, 'Engels' pause.'

[64] Feinstein, 'Pessimism perpetuated.' Equation (10) is implemented using the GDP deflator estimated by Broadberry et al., *British economic growth*. This was not available when Allen wrote his paper.

[65] Allen, 'Engels' pause.' Engels' pause comprises a period when real wages stagnated and labour's share of national income fell. Allen's subsequent work on the distribution of income as revealed by social tables also suggests that labour's share did not decline in the first half of the nineteenth century, 'Class structure.'

[66] Real consumption earnings are estimated using Feinstein's money earnings deflated by Allen's cost of living index reported in 'Pessimism preserved.'

compared with 134.9 for the GDP deflator. In turn, the reason for this discrepancy is that industrial prices were lower in 1830 than they had been in 1770 while agricultural prices were considerably higher. Industrial prices, notably those of textiles and metals, which were relatively unimportant for the cost of living for workers, benefited much more from TFP growth during the industrial revolution (cf. Table 5) than did agricultural prices which had a large impact. The bottom line is that technological progress raised labour productivity by more than real consumption earnings because it was biased towards exportable manufactures.[67]

It is, of course, well-known that demographic pressure intensified considerably in the later eighteenth and early nineteenth centuries. It is important to recognise that this potentially had significant implications for real wages, as Wrigley has emphasized. In his view, real wage growth of around 0.5 per cent in the early decades of the industrial revolution was a 'truly remarkable achievement' at a time of unprecedented population growth, which a century earlier would have precipitated large falls in real wages.[68] This assessment was based on the work of Wrigley and Schofield whose interpretation of English population history from the mid-sixteenth to the late eighteenth century was that population growth of about 0.5 per cent per year was the maximum compatible in the long run with real wages not falling.[69]

The relationship between real wages and population can be formulated as follows:

$$\text{Log}(w/p) = \alpha - \beta\text{Log}(pop) + \rho t + \varepsilon \qquad (11)$$

This captures the interaction between labour demand and labour supply. The demand for labour has an elasticity of $-\beta$ with respect to the real wage and shifts outward at the rate ρ/β.[70] If population grows at ρ/β, the real wage is constant but any rate higher than this puts downward pressure on real wages. If population is stationary, then the real wage grows at ρ. ρ will be positive if technological progress raised labour productivity so, for example in the event of Smithian growth. The Industrial Revolution would be expected to lead to an increase in ρ/β.

In this framework, Wrigley and Schofield can be regarded as believing that ρ/β was 0.5 per cent per year in pre-industrial-revolution England. Econometric methods have delivered similar results; Lee and Anderson and Crafts and Mills obtained estimates of 0.47 per cent per year for 1600-1795 based on the real wage series used by Wrigley and Schofield and 0.40 per cent per year for 1570 to 1760 based on the real earnings series constructed by Humphries and Weisdorf, respectively.[71] Each of these papers also found a substantial rise in ρ/β subsequently; Crafts and Mills' estimate, which is based on Feinstein's real earnings series, was 1.49 per cent per year for 1761 to 1850.

The obvious implication of these estimates is that the population growth experienced from 1750 to 1850 far exceeded the rate with which the early-eighteenth century economy could cope. Demographic pressure on this scale would have devastated real wages so Wrigley's praise for the

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[67] Leunig and Voth, 'Spinning welfare', estimated that foreign rather than domestic purchasers realised over half the gains in consumer surplus which accrued as technological progress reduced the price of cotton textiles.

[68] Wrigley, 'Coping with rapid population growth', p. 31. The population of England rose from 5.92 million in 1751 to 8.67million in 1801 and 16.73 million in 1851, a growth rate of 0.77 per cent per year 1751-1801 and 1.32 per cent per year for 1801-51, Wrigley et al., *English population history*.

[69] Wrigley and Schofield, *Population history*.

[70] This assumes labour supply is inelastic. More generally, β will be a combination of demand and supply elasticities.

[71] Lee and Anderson, 'Malthus in state space'; Crafts and Mills, 'The race'; Humphries and Weisdorf, 'Unreal wages.' Crafts and Mills also report estimates for alternative real wage series which are slightly lower.

early-nineteenth century economy seems to be justified. Moreover, if the acceleration of population growth was exogenous rather than a consequence of the industrial revolution, then it would be reasonable to argue that the industrial revolution averted a collapse of living standards. In that case, the working class benefited much sooner than Feinstein allowed.

It is unlikely that the decline in mortality resulted from improvements in nutrition associated with the growth of real earnings or, more specifically, can be attributed to the industrial revolution. Recent reviews of the evidence on food supplies per person have concluded that they probably decreased somewhat in the later eighteenth and early nineteenth centuries and recent surveys of the evidence on nutritional status, as reflected in declining heights, have come to similar conclusions.[72] Insofar as industrialization per se had an impact on mortality, it was a negative one through the adverse impact of urbanization.[73] Much reduced mortality from epidemic diseases including typhus and smallpox, the latter being largely eliminated by vaccination, was the main component and can be regarded as exogenous.[74]

If endogeneity of lower mortality can be ruled out, the exogeneity of increased fertility is more doubtful. Changes in nuptiality, with a reduction in age at first marriage and in those who never married, were central to rising birth rates, but they were supplemented by increased illegitimacy and fewer stillbirths. It is marriage behaviour which has been most closely linked to the Industrial Revolution, notably by Goldstone, who argued that it changed as a result of better employment opportunities for the proletarianized labour force.[75] This argument has not, however, met with general approval. Boyer found evidence that payment of children's allowances under the Old Poor Law accounted for much of the increase in fertility between 1780 and 1820, while Wrigley and his co-authors stressed that the downward trend in age at marriage was very similar across diverse economic and geographical areas.[76] Griffin has suggested that the evidence relating changes in nuptiality to economic factors is far from robust and argued that changing cultural and social norms played a significant role.[77] On balance, the evidence suggests that the fertility shock was probably not primarily a response to the industrial revolution but the jury is still out.

The hypothesis that exogenous demographic shocks led to a surge in population growth is supported by econometric analyses. Estimates of structural models of economic-demographic interactions have found that the pre-industrial economy was subject to big shifts in the intercepts of equations relating fertility and (inversely) mortality to the real wage including in the late eighteenth century.[78] Crafts and Mills find that these shocks raised the crude birth rate and lowered the crude death rate by about 6 percentage points in each case between the 1760s and the 1820s. In the circumstances of an earlier period, they would have decimated real wages, in the context of the industrial revolution the implication was that they severely inhibited the scope for productivity growth to raise real wages.

Crafts and Mills quantified the impact of the demographic shocks by simulating their structural model; their results are reported in Table 11. The baseline simulation shows that their model generally does

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[72] Kelly and O'Grada, 'Numerare est errare"; Meredith and Oxley, "Food and fodder"; Cinnirella, "Optimists or pessimists'; Komlos and Küchenhoff, 'Diminution'.
[73] Williamson, *Coping with City Growth*; Woods, *Demography*.
[74] Davenport, 'First stages.'
[75] Goldstone, 'Demographic Revolution.'
[76] Boyer, "Malthus was right'; Wrigley et al., *English population history*.
[77] Griffin, 'A conundrum resolved?'
[78] Lee and Anderson, 'Malthus in state space'; Crafts and Mills, 'The race.'

a reasonable job of tracking real earnings.[79] The remaining columns show the effect of suppressing the shocks. In each case, there is a sizeable impact. In the absence of both these shocks, the model estimates that average real earnings growth would have been increased by 1 percentage point per year between 1780 and 1840 by which time real earnings would have been more than double the 1780 level.

These simulations suggest that demographic shocks which raised population growth to a new high during the Industrial Revolution undermined its potential to raise real wages. They support Wrigley's assessment that the modest real wage growth of the early nineteenth century was 'a truly remarkable achievement.'[80] The threat to real earnings from earlier marriage and lower mortality from epidemic disease was substantial. The economic benefits of the Industrial Revolution for the working class were realised straightaway through the avoidance of big reductions in living standards. Technology narrowly won the race with population.

That said, victory had a strong regional dimension which illustrates this conclusion very well. While real wages in the industrializing north rose in the face of rapid population growth, real wages in the agricultural south fell as population increased more modestly but at rates above the pre-1760 'speed limit'. For example, between 1770 and 1840 population in Lancashire rose by about 370 per cent and real wages increased over the same period by 23 per cent while in Dorset population rose by only 80 per cent but real wages fell by 25 per cent.[81]

The estimates in Table 11 are indicative rather than definitive and are derived from a rather basic model which embodies strong assumptions. In addition to those relating demography already discussed, it must be recognised that it is assumed that population growth has no effect on the rate of technological progress. Presumably, both Allen and Acemoglu might dispute this point but with conflicting expectations about the direction of the effect. For Allen, the negative impact of population growth on real wages would reduce innovative effort whereas the opposite applies to Acemoglu who would expect a positive response to increased supplies of unskilled labour. In the former case, the adverse effects of population growth on real wages are intensified, in the latter case they are alleviated.

In sum, there is a danger that the literature has become unduly pessimistic about the implications of productivity growth for real consumption earnings and labour's share of national income. Clearly, it is important to think in terms of counterfactuals especially concerning the implications of population growth but the interactions between demography and technology are not yet well understood.

7. The Productivity Slowdown of the 1870s

Although productivity growth during the industrial revolution did not experience the acceleration that was once supposed, it may have marked a transition to an economy capable of modern economic

[79] The exception to this is 1800 where temporarily high grain prices reduced real wages significantly.
[80] Wrigley, "Coping with Rapid Population Growth", p.31.
[81] Population estimates are taken from Mitchell, *British historical statistics* and Wrigley, 'English county populations'; money wage data are for agricultural labourers as reported by Hunt, 'Industrialization.' There are no county-level cost-of-living indices so the estimates for real wages in the text have used Feinstein's national index as a deflator. They are admittedly rough and ready but the basic point is undoubtedly correct.

growth, i.e., where sustained economic growth based on technological progress became the norm; this is the vision offered by Mokyr.[82]

As noted earlier, the essence of the Industrial Revolution for Mokyr is that it entailed the invention of a new method of invention. This was based on empiricism rather than scientific understanding. The example of steam-engine technology is a good case in point. Nuvolari and Verspagen detail the progress made in raising fuel efficiency in Cornish pumping engines via detailed observation and reporting of the performance of different designs. Systematic data collection was used as a substitute for theoretical understanding. An important implication was that this localized technological learning did not diffuse to other locations and branches of industry.[83]

It is important, however, not to exaggerate what was achieved during the Industrial Revolution. A striking feature of the estimates in Table 3 is the weakness of TFP growth in the period 1873 to 1913. When growth accounting is conducted using hours worked and identifying a separate contribution from labour quality, TFP growth averaged 0.1 per cent per year. The contribution of labour quality was strong throughout the period as years of schooling rose steadily.[84] It is not correct to see the slowdown in TFP growth as a blip at the start of the twentieth century as might be thought by a reader of Feinstein et al.[85] As with the example of steam engines discussed above, slow TFP growth after 1873 suggests that the capabilities of the method of invention characteristic of the industrial revolution period were actually quite limited. The most likely late-nineteenth century failure was in not improving the national innovation system.[86]

This period of slow TFP growth coincides with the second industrial revolution which might be defined as the invention of another (superior) method of invention, in this case based on applied science and the innovation of the industrial research and development (R & D) laboratory in contrast to the Industrial revolution which had little or no scientific base.[87] In terms of Figure 1, the second industrial revolution delivered further increases in λ, σ and q but Britain was not well placed to realise this potential.

In the era of the second industrial revolution, technological leadership moved inexorably to the United States which exhibited a higher growth potential than contemporaneous or industrial revolution Britain. By now, invention relied a lot more on formal education. Whereas only 12 per cent of 'great inventor' patents were granted to people with science or engineering training in pre-1845 birth cohorts in the United States this increased to 32 per cent for the 1846-65 cohort and to 60 per cent for the 1866-1885 cohort.[88] Ultimately, the United States made larger investments in advanced human capital and the knowledge economy which would become central to technological progress in the 20th century; university students were 0.07 per cent of the population and R and D was 0.02 per

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[82] 'The Industrial Revolution went into a higher gear after 1800, not only continuously improving those inventions that had started the movement, but also continuously finding entirely new avenues of innovation … which made continuous technological progress the centrepiece of sustainable economic growth', *The enlightened economy*, p. 84.

[83] Nuvolari and Verspagen, 'Technical choice.'

[84] Average years of schooling for people aged 15 to 64 rose from 4.13 in 1870 to 4.97 in 1880, 5.40 in 1890, 5.84 in 1900 and 6.35 in 1910 according to the estimates in Morrisson and Murtin, 'The century.'

[85] Feinstein et al., 'The timing.'

[86] See Crafts, 'British relative economic decline' for a review of the literature on late-nineteenth century 'failure'.

[87] Or in Mokyr's words, 'It created a chemical industry with no chemistry, an iron industry without metallurgy, power machinery without thermodynamics', 'Second industrial revolution', p. 1.

[88] Khan and Sokoloff, 'Institutions and technological innovation.'

cent of GDP in the UK in 1913 compared with 0.56 per cent and 0.25 per cent, respectively, in the United States in 1920.[89]

The UK's technological performance was mediocre by European standards as is confirmed by patenting citations data which show British patents were on average of lower quality than those of France, Germany and Switzerland in the period 1870 to 1918.[90] While in 1883 the UK share of foreign patents in the United States was 34.6 per cent against 18.7 per cent for Germany by 1913 the UK share was 23.3 per cent compared with 34.0 per cent for Germany.[91]

The British government had very limited ambitions in terms of support for innovation. Although small beginnings were made in promoting scientific research, for example, through the National Physical Laboratory (1899) and the Medical Research Council (1913), public expenditure on science and technology was only 0.06 per cent of GDP in 1914.[92] This undoubtedly implied that there was too little government support for R & D, a pro-growth activity where social returns exceed private returns. An obvious contrast with the United States was the investment there by state governments in new universities with a greater emphasis on research, professional schools and industrial connections including, notably, MIT (founded in 1862) with its strengths in chemical and electrical engineering.[93]

8. Conclusions

The data available to make growth accounting estimates for Britain during the industrial revolution have improved significantly in the recent past. They provide confirmation that productivity growth during the period was not very rapid and accelerated only gradually. The growth of real GDP per hour worked only reached 1 per cent per year in the second quarter of the nineteenth century. TFP growth averaged less than 0.5 per cent per year between 1770 and 1830.

Taking labour quality into account is important in looking at the post-industrial revolution period. When this is done, it is notable that TFP growth quickly subsided from its mid-nineteenth century peak and it averaged only 0.10 per cent per year for the forty years before World War I. Measuring labour productivity on an hours-worked basis reveals that the slowdown in productivity growth started in the 1870s not after 1899. The method of invention characteristic of the industrial revolution based on systematic data collection rather than applied science had its limitations.

The debate over the explanations proposed by Allen and by Mokyr for the speeding up of technological progress during the industrial revolution has made some progress in probing the evidence but both approaches remain less than fully convincing. Their hypotheses are potentially complementary rather than mutually exclusive. It seems likely that expected profits mattered to inventors but also that an effective response to profitable opportunities depended on technical competence and access to useful knowledge. Insofar as directed technical change mattered it is important to think about the potential number of adopters of a new technology rather than just relative factor prices.

Despite recent claims to the contrary it now seems that labour's share of national income did not fall during the industrial revolution. It is notable, however, that changes in relative prices meant that real consumption earnings rose by less than real product wages. Modest growth in real earnings may be

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[89] Crafts, 'Forging ahead.'
[90] Nicholas, 'Technology.'
[91] Pavitt and Soete, 'International differences.'
[92] Pollard, *Britain's prime*.
[93] Goldin and Katz, 'The shaping.'

seen as a good outcome for workers in the context of a surge in population growth so perhaps the industrial revolution benefited them more than it appears from the raw data.

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Table 1. Accounting for Growth of Real GDP: Earlier Estimates (% per year)

	Capital Contribution	*Labour Contribution*	*Land Contribution*	*TFP Growth*	*Real GDP Growth*
Feinstein					
1760-1800	0.35 x 1.0 = 0.35	0.50 x 0.8 = 0.40	0.15 x 0.2 = 0.03	0.32	1.1
1800-1830	0.35 x 1.4 = 0.49	0.50 x 1.4 = 0.70	0.15 x 0.4 = 0.06	1.45	2.7
1830-1860	0.35 x 2.0 =0.70	0.50 x 1.4 = 0.70	0.15 x 0.6 = 0.09	1.01	2.5
Crafts					
1760-1800	0.35 x 1.0 = 0.35	0.50 x 0.8 = 0.40	0.15 x 0.2 = 0.03	0.22	1.0
1800-1830	0.35 x 1.7 = 0.60	0.50 x 1.4 = 0.70	0.15 x 0.4 = 0.06	0.54	1.9
1830-1860	0.35 x 2.5 = 0.88	0.50 x 1.4 = 0.70	0.15 x 0.6 = 0.09	0.83	2.5

Note: this table is constructed using the formula in equation (1).

Sources: Feinstein, 'Capital accumulation', adjusted to 3-factor formula using land growth as in Crafts, *British economic growth* and Crafts, *British economic growth* with revisions based on Crafts and Harley, 'Output growth.'

Table 2. Accounting for Growth of Real GDP: Modern Estimates (% per year)

a) Primal

	Capital Contribution	Labour Contribution	Land Contribution	TFP Growth	Real GDP Growth
1770-1800	0.2*1.2	0.6*1.0	0.2*0.5	0.26	1.2
1800-1830	0.25*1.7	0.6*1.3	0.15*0.1	0.38	1.6
1830-1860	0.3*2.9	0.6*1.1	0.1*0.1	0.76	2.3

b) Dual

	Profit Rate Component	***Wage Rate Component***	***Land Rental Rate Component***	***TFP Growth***
1770-1800	0.2*1.50	0.6*0.14	0.2*-0.19	0.35
1800-1830	0.25*-0.21	0.6*0.59	0.15*1.60	0.54
1830-1860	0.3*0.62	0.6*0.99	0.1*0.50	0.83

Notes:
Primal: land input growth from Allen, 'Engels' Pause' ; capital input growth from Feinstein, ' National statistics', p.454; labour input growth measured in hours worked using headcount of workers as in Table 1 adjusted to an hours-worked basis using Thomas and Dimsdale, 'Millennium', Table A54 column F for 1770 to 1830 and A54 Column AW for 1830 to 1860; GDP growth from Thomas and Dimsdale, 'Millennium', Table A8 Column B. These estimates implement equation (1).

Dual: real product wage rate derived from Thomas and Dimsdale, 'Millennium', Table A47 Columns B and R; profit rate from Crafts, 'Slow real wage growth', Table 3; land rental rate is nominal rental rate from Clark, 'Land Rental Values' deflated by GDP deflator from Thomas and Dimsdale, 'Millennium', Table A47, Column R. These estimates implement equation (4).

Factor shares from Crafts, 'Slow real wage growth', Table 3.

Source: Crafts, 'Slow real wage growth.'

Table 3. Accounting for Labour Productivity Growth (% per year)

a) Labour Quality included in TFP

	ΔY/Y	*ΔK/K*	*ΔL/L*	*Δ(Y/L)/ (Y/L)*	*Capital Deepening*	*TFP*
1700-1760	0.67	0.67	0.42	0.25	0.10	0.15
1760-1780	0.85	0.70	0.86	-0.01	-0.06	0.05
1780-1800	1.48	1.50	1.02	0.46	0.19	0.27
1800-1830	1.62	1.59	1.33	0.29	0.10	0.19
1830-1856	2.36	3.00	1.15	1.11	0.65	0.46
1856-1873	2.38	2.38	0.32	2.06	0.72	1.34
1873-1913	1.86	1.90	0.80	1.06	0.38	0.68

b) Labour Quality Taken Out of TFP

c)	*ΔY/Y*	*ΔK/K*	*ΔL/L*	*ΔLQ/ LQ*	*Δ(Y/L)/ (Y/L)*	*Capital Deepening*	*Human Capital Deepening*	*TFP**
1700-1760	0.67	0.67	0.42	0.01	0.25	0.10	0.01	0.14
1760-1780	0.85	0.70	0.86	-0.01	-0.01	-0.06	-0.01	0.06
1780-1800	1.48	1.50	1.02	-0.02	0.46	0.19	-0.01	0.28
1800-1830	1.62	1.59	1.33	0.01	0.29	0.10	0.01	0.18
1830-1856	2.36	3.00	1.15	0.13	1.11	0.65	0.08	0.38
1856-1873	2.38	2.38	0.32	0.50	2.06	0.72	0.32	1.02
1873-1913	1.86	1.90	0.80	0.90	1.06	0.38	0.58	0.10

Note: TFP* indicates that the contribution of labour quality is measured separately from TFP as in equation (6); s_k = 0.40 in 1700-1830 and 0.35 in 1830-1913. Labour quality through 1856 is based only on years of schooling as estimated by de Pleijt, 'Human capital', assuming a 6 per cent increase in labour quality per additional year, and for 1856 to 1913 is from Matthews et al., *British economic growth* including a component for occupational shifts which adds 0.1 percentage points per year to labour quality growth in 1873 to 1913 (p. 266) but excluding the impact of changes in the intensity of work.

Source: Crafts, 'The sources.'

Table 4. Steam Contributions to Labour Productivity Growth (% per year)

	Steam Capital Deepening	*Steam TFP Growth*	*Total*
1760-1800	0.004	0.005	0.01
1800-1830	0.02	0.001	0.02
1830-1850	0.16	0.04	0.20
1850-1870	0.20	0.21	0.41
1870-1910	0.15	0.16	0.31

Note: these estimates are derived using a standard growth accounting formula:

$$\Delta \ln(Y/L) = \alpha_{KO}\Delta \ln\left(\frac{K_O}{L}\right) + \alpha_{KICT}\Delta \ln\left(\frac{K_{Steam}}{L}\right) + \mu \Delta ln A_O + \phi \Delta ln A_{Steam}$$

where K_{Steam} is steam-capital inputs, A_{Steam} is TFP in production of steam power, K_O is other capital input and A_O is other TFP; Φ and μ are Domar weights for the steam and other sectors, respectively.

Source: Crafts, 'Steam.'

Table 5. TFP Growth Contributions, 1780-1860 (% per year)

	Value Added Share	***Rate of TFP Growth***	***TFP Growth Contribution***
Cotton	0.07	1.9	0.133
Woollens	0.05	0.95	0.048
Iron	0.02	0.9	0.018
Trade & Transport	0.15	0.9	0.135
Sum of 'Modernized'	0.29	1.15	0.334
Total (Primal)	1.00	0.51	0.51
Rest	0.71	0.25	0.176
Total (Dual)	1.00	0.61	0.61
Rest	0.71	0.39	0.276

Note: value added weights for 1820 based on Deane and Cole, *British economic growth*, p. 166 with industry allocated according to Crafts, *British economic growth*, p.22. Total TFP growth estimated as in Table 2.

Source: Harley, 'Reassessing' updated.

Table 6. Labour Force Shares (%)

	Agriculture	***Industry***
1759		
Deane and Cole	47.8	19.2
Crafts	48.0	23.8
Broadberry et al.	36.8	33.9
1801		
Deane and Cole	35.9	29.7
Crafts	35.9	29.7
Broadberry et al.	31.7	36.4
1851		
Deane and Cole	21.6	42.3
Crafts	21.6	42.3
Broadberry et al.	23.5	45.6

Note: the proportions of the labour force in 1759 for Crafts were obtained using the revised social table of Lindert and Williamson, 'Revising', as described in Crafts, *British economic growth*, p. 14; the proportions attributed to 'Deane and Cole' are based on the same method applied to Massie's original table since the revised social table was not available to them.

Sources: Broadberry et al., 'When did Britain', Crafts, *British economic growth* and Deane and Cole, *British economic growth*.

Table 7. Growth of Output, Labour and Output per Worker in Agriculture and Industry (% per year)

a) **Real Output Growth**

	Agriculture	*Industry*	*GDP*
1759-1801			
Deane and Cole	0.56	1.96	1.36
Crafts	0.44	1.62	1.01
Broadberry et al.	0.67	1.61	1.20
1801-1851			
Deane and Cole	1.80	3.47	2.78
Crafts	1.52	2.47	1.92
Broadberry et al.	0.81	2.78	1.88

b) **Labour Force Growth**

	Agriculture	*Industry*	*GDP*
1759-1801			
Deane and Cole	0.11	1.86	0.81
Crafts	0.06	1.36	0.81
Broadberry et al.	0.42	0.99	0.78
1801-1851			
Deane and Cole	0.43	2.17	1.42
Crafts	0.43	2.17	1.42
Broadberry et al.	0.65	1.71	1.26

c) **Labour Productivity Growth**

	Agriculture	*Industry*	*GDP*
1759-1801			
Deane and Cole	0.45	0.10	0.55
Crafts	0.38	0.26	0.20
Broadberry et al.	0.25	0.66	0.42
1801-1851			
Deane and Cole	1.37	1.30	1.36
Crafts	1.09	0.30	0.50
Broadberry et al.	0.16	1.07	0.62

Sources: derived from Broadberry et al., *British economic growth*; Crafts, *British economic growth* and Crafts and Harley, 'Output growth'; Deane and Cole, *British economic growth*.

Table 8. Tweakers and Implementers

	Whole Sample (%)	***Textiles (%)***
University	15	1
Apprenticed	40	17
Schooled	7	3
None/Unknown	41	80
Publishers	13	4
Society Members	14	3
Publisher and Society Member	25	2

Note: ‘tweakers’ get the bugs out of inventions while ‘implementers’ construct, install and operate them.

Source: Meisenzahl and Mokyr, ‘Rate and direction.’

Table 9. Rates of Growth of Real GDP/Worker and Real Earnings (% per year)

	Real GDP/ Worker	*Real Consumption Earnings*	*Real Product Wages*
1770-1800	0.43	0.30	0.14
1800-1830	0.31	0.15	0.59
1830-1860	0.92	1.01	0.99

Note: real consumption earnings are money wage earnings deflated by the cost of living index constructed by Allen, 'Pessimism preserved', whereas real product wages are money wage earnings deflated by the GDP deflator. The real earnings and real product wages are 5-year averages centred on the end-point dates.

Source: Crafts, 'Slow real wage growth.'

Table 10. Factor Shares (%GDP)

	Labour	*Land*	*Capital*
1770	61.0	21.8	17.2
1780	56.8	21.4	21.8
1790	57.1	19.8	23.1
1800	55.8	18.3	25.9
1810	56.4	16.3	27.3
1820	59.0	15.8	25.2
1830	60.7	15.1	24.2
1840	59.2	12.5	28.3
1850	65.3	10.5	24.2
1860	60.2	8.5	31.3

Source: Crafts, 'Slow real wage growth.'

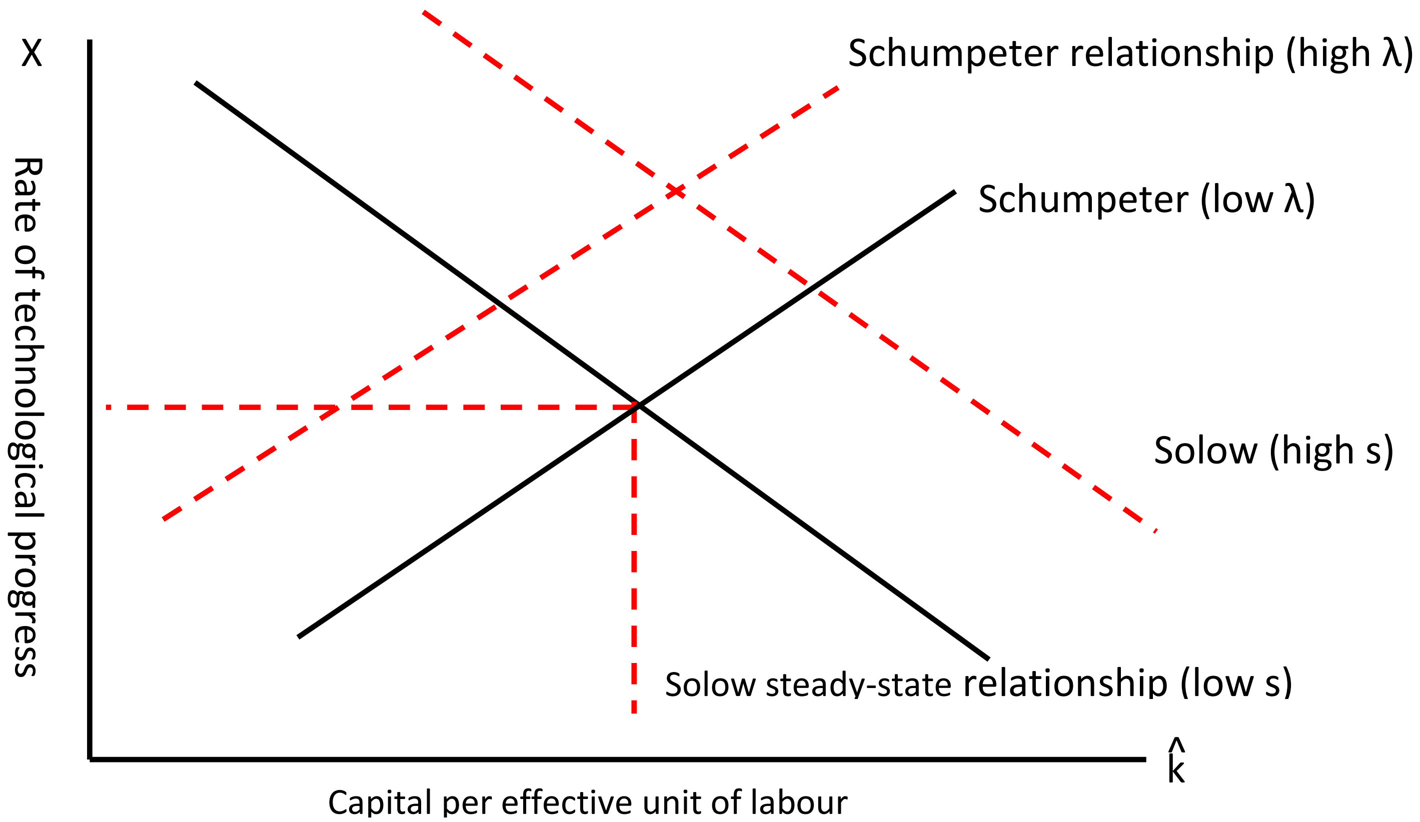
Table 11. Actual and Simulated Real Earnings, 1780-1840: (1780 = 100)

	Actual (5-year average)	*Baseline Simulation*	*Mortality Shock Removed*	*Fertility Shock Removed*	*Both Shocks Removed*
1780	100.0	103.6	103.3	108.9	108.2
1800	102.7	113.5	114.8	134.9	136.2
1820	110.8	112.5	119.7	160.5	171.1
1840	117.6	113.5	135.2	179.9	214.8

Note: all estimates are derived using Feinstein's real earnings series, 'Pessimism perpetuated' with ρ/β assumed = 1.49 per cent per year. Removal of shocks is implemented by fixing intercepts of estimated fertility and mortality equations at 1760 values, see the text.

Source: Crafts and Mills, 'The race.'

Figure 1: Endogenous Growth



Appendix 1

Modern growth economics based on the idea of endogenous innovation makes TFP growth endogenous. The key ideas are captured in Figure 1, in which x is the rate of (labour-augmenting) technological progress and $\hat{k}$ is the capital to effective labour ratio.

The downward-sloping (Solow) line represents the well-known inverse steady-state relationship between technological progress and the capital-intensity of the economy for a given savings rate in the neoclassical growth model.

The intuition for this is as follows. Steady-state growth means that the rate of growth of the capital stock is equal to the rate of growth of the labour force plus the rate of growth of labour-augmenting technological progress ($\Delta K/K = \Delta L/L + x$) and $\Delta K/K = sY/K$. So, capital stock growth is inversely related to the average product of capital. In the neoclassical model, it is assumed that marginal and average product of capital fall as the capital to labour ratio increases so the rate of growth of the capital stock is inversely related to the capital to labour ratio. In equilibrium faster technological change requires faster capital stock growth and for a given value of s this requires a lower capital to labour ratio. Hence the slope of the Solow line

The upward-sloping (Schumpeter) line reflects the endogeneity of technological progress based on the assumption that a larger market increases innovative effort because it is potentially more profitable since success will be rewarded by greater sales. With more capital per unit of effective labour there will be higher income per person so the Schumpeter line is upward-sloping.

The equilibrium rate of technological progress is established by the intersection of these two lines and, in turn, this determines the rate of economic growth.

Figure 1 implies that the rate of innovation increases when either the Solow and/or the Schumpeter line shifts upward. In the former case, this will be the result of an increased rate of investment which in this model does have growth rate effects. In the latter case, this will be the result of an increase in innovative effort, together with the productivity and impact of that effort, for any given market size. This will in general reflect institutions and policies but, crucially for Mokyr's argument, the method of invention.

Appendix 2

Table 12. Internal Rate of Return on Purchase of Spinning Jenny, 1770s (%)

	Cost of Jenny			
	576d	706d	840d	1450d
Wages				
8	82.9	65.5	53.1	23.8
6.25	62.2	48.4	38.0	13.5
6	59.2	45.9	36.1	12.0
4.66	43.0	32.1	24.0	2.5
3.8	32.1	22.7	15.5	-4.8

Table 12 reports calculations of the internal rate of return based on equations (8) and (9) for several price and wage configurations retaining Allen's assumptions that YD = 100 and P = 3.

The original data used by Allen are daily wages = 6.25d, price of 24-spindle jenny = 840d in England and wages = 4.66d, price of jenny = 1450d in France. These generate a rate of return of 38.0 per cent in England and 2.5 per cent in France. It is worth noting that if the price of a jenny in France was the same as in England at wages = 4.66d the rate of return would have been 24.0 per cent. Low wages on their own are not enough to push France below the 15 per cent threshold.

Styles argues that more accurate French data indicate that wages in Normandy were similar to those in Lancashire.[94] Based on the work of John Holker, he suggests that a reasonable price per spindle in England was 24d and in France in 1776 was 29.4d.[95] This would imply a price for the benchmark 24-spindle jenny of 576d in England and 706d in France. In both cases, these are much cheaper than Allen's estimates. Using these assumptions, adopting the jenny would be highly profitable in both countries with rates of return of 62.2 per cent in England and 48.4 per cent in France.

In later work, Allen adopted some of Muldrew's estimates of English spinners wages.[96] These include 3.8d for wages in 1687 and 8d for wages in 1750. Humphries and Schneider disputed these figures and their work suggests that 3.8d may still have obtained around the time of Hargreaves's invention.[97] At 8d, not surprisingly we see a massive rate of return of 82.9 per cent in England at a jenny price of 576d. Interestingly, even at 3.8d adoption would be rational except if the price of a jenny was as high as Allen thinks for France and a rate of return of 32.1 per cent would obtain at a jenny price of 576d. On this basis, it would seem relevant to ask why the invention of the jenny was so long delayed.

The bottom line of these permutations is that it is very highly likely that adopting the spinning jenny would have been rational both in Britain and in France. However, this conclusion is reinforced if we drop the assumption maintained until now that output was fixed and that a productivity improvement was simply matched by reductions in hours worked with the jenny lying idle for much of the time. This seems implausible and has been challenged by Gragnolati et al.[98] They suggest that a reasonable alternative assumption would be that labour inputs are fixed and the productivity gain of adopting the jenny accrues in additional output. For all the combinations of wages and jenny prices considered above, I calculate that the lowest rate of return would be 41.1 per cent while the highest would be

[94] Styles, 'Robert Allen's spinning jenny.'
[95] Personal email communication on 10/08/2020.
[96] Allen, 'High wage economy'; Muldrew, '"Th' ancient distaff".'
[97] Humphries and Schneider, 'Losing the thread.'
[98] Gragnolati et al., 'Spinning jenny.'

267.8 per cent. At wages of 6.25d in both countries and jenny prices at 576d and 706d, the rates of return would be 207.0 per cent and 167.0 per cent in England and France, respectively. So, a relaxation of the fixed output assumption just reinforces the conclusion that inventing the jenny was very attractive in both countries.

Nevertheless, all the above calculations may be beside the point. Styles suggests that the Lancashire and Normandy cotton spinning industries are very different such that it would not have made sense to try to invent the spinning jenny in France.[99] He argues that the spinning jenny only makes sense for spinning higher-count fine yarn not the coarse yarn spun in France. The French industry used raw Levant cotton, did not benefit from the putting-out system, and could not easily imitate the output mix and industrial organization of Lancashire.

[99] Styles, 'Rise and fall.'