PRODUCTIVITY GROWTH IN THE INDUSTRIAL REVOLUTION:

A NEW GROWTH ACCOUNTING PERSPECTIVE

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Abstract

The issue of why productivity growth during the British industrial revolution was slow despite the arrival of famous inventions is revisited using a growth accounting methodology based on an endogenous innovation model and the perspective of recent literature on general purpose technologies. The results show that steam had a relatively small and long-delayed impact on productivity growth when benchmarked against later technologies such as electricity or ICT. Even so, technological change including embodiment effects accounted entirely for the acceleration in labor productivity growth that allowed the economy to withstand rapid population growth without a decline in living standards.

Growth accounting has played an important role in the reassessment of British economic growth during the industrial revolution and the emergence of the Crafts-Harley view.[1] The results obtained in recent analyses have suggested that total factor productivity (TFP) growth was quite modest in the decades following the cluster of major inventions (steam engine, spinning mule, puddling etc.) that are identified with the onset of faster industrial growth and much less in the early nineteenth century than was once believed.

Table 1 summarizes developments in growth accounting estimates for the industrial revolution period. The change implied by the Crafts-Harley view can be seen in the difference between Feinstein's early results based on older national income data and those of Crafts based on the newer estimates. The estimates by Antras and Voth confirm that the Crafts-Harley revisions are plausible using an independent procedure based on the price dual approach to TFP measurement.

Mokyr has pointed out the implications of the revised TFP growth estimates as follows. "The apparent dominance of invention over abstention, one of the most striking findings of the New Economic History, seems less secure now than it did a decade ago. Clearly it is unwarranted to expect that major technological breakthroughs will lead to more or less simultaneous increases in productivity."[2]

How can one reconcile slow macroeconomic TFP growth with spectacularly successful microeconomic innovations in several important industrial sectors such as cotton textiles and the iron industry? At one level an answer is provided by the disaggregated growth accounting results put forward by Harley which suggest that much of the economy, notably including the service sector except for transportation, experienced at best very slow TFP growth.[3]

At another level of explanation, recourse might be had to the recent literature on General Purpose Technologies (GPTs).[4] A GPT can be defined as "a technology that initially has much scope for improvement and eventually comes to be widely used, to have many uses, and to have many Hicksian and technological complementarities".[5] Electricity, steam, and information and communications technology (ICT) are usually seen as among the most important examples. Clearly, it is to be expected that a new GPT will have a substantial positive impact on the rate of TFP growth. However, a key theme of these models of economic growth is that the initial impact of a GPT is either negligible or even possibly negative and that the delay before TFP growth rises appreciably may be considerable. Thus, productivity growth in the industrial revolution may have benefited very little from the arrival of steam power until relatively late in the day.

These arguments acquire some credibility when the results of a separate stream of research into the social savings of technological change are recalled. Von Tunzelmann estimated that, if James Watt had not invented the improved steam engine in 1769, the national income of Great Britain in 1800 would have been reduced by only about 0.1 per cent.[6] Similarly, Hawke found that the social savings of railways in England and Wales in 1850 amounted to £9.7 million when the British gross domestic product was £523 million.[7] The later US experience of electricity also lends support. While the excitement of the electrical age arrived in the 1880s, the main (very substantial) productivity impact came only in the 1920s when the possibilities for re-design of the factory were realized.[8]

Alternatively, perhaps more attention should be given to the choice of growth accounting methodology. In particular, the development of endogenous growth theory may be thought to imply that the traditional growth accounting techniques based on the neoclassical (Solow) growth model are no longer appropriate. This view has been put forward by Greasley and Oxley whose results are also reported in Table 1. Their approach, based on assuming two factors of production (capital and human capital) which together comprise 'broad capital', leads them to conclude that it "support[s] the endogenous model by removing the need for TFP to play a substantive role in industrial revolution growth".[9] This is clearly not a way to rehabilitate rapid technological change or 'ingenuity rather than abstention' as the central theme of the industrial revolution.

The methodology proposed by Greasley and Oxley does not, however, adequately reflect the new growth economics and assumes a production function that has no empirical justification.[10] Moreover, their results imply an astonishing rate of return to very modest increases in formal schooling, as is demonstrated in calculations made by Mitch.[11] While the Greasley and Oxley attempt to revise growth accounting should not be taken seriously, there are other, more promising, possibilities to be explored.

Barro has set out a method based on an endogenous innovation model of economic growth. This approach does not seek to abolish TFP growth but rather argues that measured TFP growth generally underestimates the contribution made by technological change to growth.[12] It attributes a larger proportion of growth to innovation by taking explicit account of its embodiment in new varieties of capital goods and might well be regarded as an appropriate way to address the impact of the new technologies of the industrial revolution, a time famous for new machines. As Feinstein put it, "many forms of technological advance ... can only take effect when 'embodied' in new capital goods. The spinning jennies, steam engines, and blast furnaces were the 'embodiment' of the industrial revolution".[13] Growth accounting along these lines has already been widely used to investigate the impact of ICT, the new GPT, on late twentieth century American economic growth.[14] These studies all seek to capture the growth contribution of ICT by estimating components based on ICT capital in use as well as TFP growth.

In the light of this discussion, this paper re-examines the TFP growth paradox of the British industrial revolution using a revised growth accounting methodology similar to those featured in the recent literature on ICT. This will permit not only a reappraisal of the growth contribution of technological change but also an assessment of the role played by steam as a GPT.

GROWTH ACCOUNTING METHODOLOGY

The traditional neoclassical growth accounting methodology captures a contribution to growth from exogenous technological change in the Solow residual estimate of TFP growth. With the standard Cobb-Douglas production function and competitive assumptions

$$Y = AK^{\alpha}L^{1-\alpha} \tag{1}$$

the Solow residual is computed as

$$\Delta A/A = \Delta Y/Y - s_K \Delta K/K - s_L \Delta L/L \tag{2}$$

where s_K and s_L are the factor income shares of capital and labor respectively. Variants of this approach, including the price dual technique, have been the standard method of estimating the contribution of technological change to growth during the British industrial revolution, as was reported in Table 1. Equation (2) can be converted to an expression that accounts for growth of labor productivity as follows:

$$\Delta(Y/L)/(Y/L) = s_K\Delta(K/L)/(K/L) + \Delta A/A \quad (3)$$

Growth accounting techniques are, however, based on models of economic growth and, in particular, are derived from the specification of the aggregate production function. If an endogenous growth model is assumed, the contribution of technological change will not generally be equal to the Solow residual. Barro and Sala-i-Martin formulate a version of an endogenous innovation growth model which illustrates this point and is also a useful tool for reappraisal of growth during the industrial revolution.[15] In their specification

$$Y = AL^{1-\alpha}NK^{\alpha} \quad (4)$$

where N is the number of varieties of capital goods each of which in equilibrium is employed at the same level and can be measured in a common unit. This can be written as

$$Y = AL^{1-\alpha}(NK)^{\alpha}N^{1-\alpha} \quad (5)$$

where (NK) is the aggregate flow of capital services. Equation (5) implies that diminishing returns set in when K increases for given N but not when N rises for given K. Therefore technological progress in the form of continuing increases in N can provide the basis for endogenous growth.

The formula for output growth based on equation (5) is

$$\Delta Y/Y \;=\; \Delta A/A \;+\; (1-\alpha)\Delta N/N \;+\; s_L \Delta L/L \;+\; s_K(\Delta N/N \;+\; \Delta K/K) \qquad (6)$$

where the standard computation for TFP gives $\Delta A/A \;+\; (1-\alpha)\Delta N/N$.

Thus part of the contribution of technological change, i.e., $\alpha\Delta N/N$, is attributed to capital. On these assumptions, TFP growth underestimates the impact of technological change on growth.

A variant of this approach has been adopted by practitioners in the literature on the role of ICT in economic growth. Thus Oliner and Sichel identified the contribution of innovations in ICT to growth of labor productivity as coming through three types of ICT capital deepening (computer hardware, software and communication equipment) weighted by the shares of these types of capital in income and through TFP growth in ICT production weighted by its share in gross output [16] Oliner and Sichel's results are summarized in Table 2 which is useful both to illustrate this method of growth accounting and as a benchmark against which steam can be compared. For this latter purpose it may be that the period prior to the mid-1990s is the most relevant since 1996-9 is perhaps seriously affected by cyclical influences.

The results reported in Table 2 can be summarized for our purposes as follows. The total contribution of ICT to labor productivity growth is estimated to have been 0.61 percentage points per year from 1974-90 and 0.74 in 1991-5. In each case the larger part accrues from capital deepening rather than TFP growth. It is noticeable that the capital income and output shares are both small even at the end of the 1990s but rise over time. This restrains ICT's initial impact notwithstanding sustained double digit annual growth rates both of ICT capital stock and of TFP in ICT production.

The model assumed by Oliner and Sichel and thus the estimates in Table 2 may not, however, do full justice to ICT as a GPT. Another strand of endogenous growth theory posits spillover effects on TFP elsewhere in the economy through technological complementarities, as in the case of electricity and factory design in the 1920s.[17] It is widely claimed that TFP spillovers from ICT started to materalize in the later 1990s (through reorganization effects in particular) but at present there exist no quantitative estimates of their macroeconomic impact.[18]

New economic historians traditionally measured the contribution of a new technology to economic growth using the concept of social savings. This was most famously applied to the impact of the railroad in many countries by authors following the methodology developed by Fishlow and Fogel.[19] The social saving is usually computed as an upper bound measure of the gain in consumer surplus from the fall in costs allowed by the new technology. In the case of railroads the alternative might be canal transport. Thus:

$$SS = (p_W - p_R)q_R \qquad (7)$$

where SS is social saving, p_W and p_R are the prices charged for water and rail transport, respectively, and q_R is the quantity transported by rail in the year of observation.

If demand is not perfectly price inelastic this is, of course, an overestimate of the true social saving. If perfect competition prevails in the transport industry, the social saving is also equal to the total resource cost saving and if, in addition, the rest of the economy is also perfectly competitive throughout, then the transport benefit is also equal to the gain in real income.[20] This is the interpretation that Fogel gave to the social saving.[21]

Harberger reminded us that TFP growth can be interpreted as real cost reduction and the price dual measure of TFP confirms that the fall over time in the real cost of railroad transport under competitive conditions is also equal to TFP growth.[22] Since railroads will only be introduced at the point where they can offer transport at the same cost as canals, the social saving measure should approximate to the railroad TFP contribution in a growth accounting exercise of the Oliner and Sichel type, provided the same volume of output is chosen to compute the estimate. Indeed, this equivalence is exactly how Foreman-Peck extended Hawke's social savings estimate for British railways to 1890.[23]

The price dual measure of TFP growth equivalent to (2) is

$$\Delta A/A = s_K \Delta r/r + s_L \Delta w/w - \Delta p/p \qquad (8)$$

where r is the profit rate, w is the wage rate and p is output price. Thus, when input prices are constant, TFP growth equals the rate of price decline.

Using this result, the rail social saving in year t compared with the year of introduction, t − 1, expressed as a fraction of rail revenue is

$$(p_{t-1} - p_t)q_t/p_tq_t = p_{t-1}/p_t - 1 = A_t/A_{t-1} - 1 \qquad (9)$$

or expressed as a fraction of GDP is

$$(A_t/A_{t-1} - 1)*(p_tq_t/GDP_t) \qquad (10)$$

Rail social savings as a proportion of GDP are revealed to be the percentage change in TFP in the rail industry multiplied by the ratio of rail output to GDP.

The social saving approach is then equivalent to taking only the TFP and not the capital contribution of an innovation. The logic of this is quite clear in terms of Fogel's search for the indispensable element that railroads gave to the economy and his desire to kill the myth of indispensability. Railroad capital earned a normal profit equal to its opportunity cost. If the capital were not invested in railroads, it would be invested in something else that would deliver an equal return.

Growth accounting attempts to measure the realised results of investment that has taken place and addresses the question 'how much did the new technology contribute?' rather than the question 'how much more did it contribute than an alternative investment might have yielded ?' which is the focus of the social saving. In addition, the new growth accounting is based on an endogenous innovation growth model in which new technology is embodied in capital equipment. The implicit assumption is that, in the absence of the innovation, the economy would both have a lower TFP growth rate and a quantity of capital lower by the whole amount of the new capital goods in which the technology is embodied.

It seems likely that many economists would instinctively believe in models that would imply answers somewhere between the growth accounting and social savings methodologies. Thus some would consider at the macro-level that investments of the size typically made in major new technologies could not have been made in alternative projects without depressing the rate of return at least somewhat, while others will predict that the adoption of new technologies precipitates the exit of some old capital goods that would have survived. Thus, it will be useful to have both standards of comparison available as benchmarks.

Had the relationship between the social savings and TFP growth as measured by traditional growth accounting been more widely recognized, it seems likely that the TFP growth findings of the Crafts-Harley view would have been anticipated. Given that major innovations such as the steam engine and the railway had rather modest social savings, it should have been no great surprise that aggregate TFP growth was not very fast.

GENERAL PURPOSE TECHNOLOGIES AND THE INDUSTRIAL REVOLUTION

This section seeks to implement the Oliner and Sichel growth accounting framework for steam during the British industrial revolution. The analysis will rely heavily on early work in cliometrics and will convert the social savings estimates of those days into a growth accounting format. It will also, however, provide estimates of the impact of steam capital-deepening on labor productivity growth.

Table 3 reports the results of a compilation of information from existing studies on the impact of stationary steam engines used in industry and of railways (a sector wholly dependent on steam power) into a growth accounting format comparable with that for ICT in Table 2. The data on steam engines is incomplete, especially for the period between 1800 when Watt's patents expired and 1838 when the first returns under the Factory Acts were made. Nevertheless, there is general agreement on the broad picture of the use of steam power. In 1800 there were about 35,000 and in 1830 about 160,000 steam horsepower and even in 1870 only about 1.7 million steam horsepower were in use, representing about 2.5 per cent of the capital stock.[24] Steam power was intensively used in textiles, the iron industry and coal mining but important sectors of the economy including agriculture and the tertiary sector outside of transport were virtually untouched by it.[25] For a very long time water power remained cheaper for most users.[26] Thus the capital deepening contribution reported in Table 3 is quite small.

Although Watt's steam engine represented an important advance, from 1800 to about 1840 there was little further advance and the capital costs of steam engines did not fall – there was no equivalent to Moore's Law in operation then.[27] There followed a period of further advance; many steam engines were upgraded to work at higher pressures and the price of steam power to the user had approximately halved by the mid-1850s.[28] Insofar as this represented an upgrading in quality in the steam engine, it is (imperfectly) captured in the data which after 1860 are for 'indicated' horsepower. There are, however, no hedonic prices for steam engines with which to refine the capital-deepening estimate.[29]

Table 3 shows that steam's impact on labor productivity growth was less than 0.01 percentage points throughout the period 1760-1830 with a negligible role for TFP growth. An appreciable contribution to growth from steam only came during the railway age which is conventionally dated from the opening of the Liverpool and Manchester Railway in 1830. A massive investment in railway construction ensued although the profits obtained were quite modest. Railway technology developed rapidly but the social savings estimates of Hawke, whose results are incorporated in Table 3, translate into a TFP contribution to raising overall labor productivity of only 0.05 percentage points per year in the period 1830-60. Even with the capital-deepening component, steam's contribution to labor productivity growth in these years was only 0.24 percentage points per year.

Table 3 includes estimates of the contribution from capital deepening and own TFP growth but does not, however, include any estimate of TFP spillovers from steam. With regard to railways, this was considered very explicitly in the social savings calculation made by Hawke who firmly rejected the notion that these were important.[30] The chief underpinning for this finding is that railways seem to have had very little impact on location decisions in the mid nineteenth century in an economy which had already adapted to canals.

Where the steam engine is concerned, the situation is more complicated. Von Tunzelmann examined the impact of steam power on technological progress in the textile industries where the main effects were most likely to be found. He noted that all the famous advances of the industrial revolution period were originally developed for other forms of power; if there were important technological complementarities, he suggested that they only came late in the day, in the period 1847 to 1860.[31] This suggests that over the whole period, 1780-1860, any such contribution to the average annual productivity growth rate would have been very small.

Table 3 shows evidence of the classic GPT phasing of productivity growth effects but with a very elongated first negligible-impact phase and a modest growth contribution even after 1830. It may be that to find the strongest impact of steam on growth would require research into a later period when steam horsepower rose from under 2 million in 1870 to 9.65 million in 1907 and when steam's contributions to globalization through transport cost reductions were considerable.[32] Taken at face value, these results suggest that slow TFP growth during the industrial revolution, especially prior to 1830, can be understood to a large extent in terms of the weakness of the productivity contribution of the most prominent GPT of the day, steam. This should not be a surprise to anyone familiar with the early cliometrics literature which highlighted how small were the initial social savings of the steam engine and the railway.[33]

The most celebrated instance of a delayed productivity impact from a GPT is the case of electricity which was highlighted in a much-cited paper by David who stressed that its big impact on productivity did not materialize until the 1920s.[34] Table 4 facilitates comparison of these episodes by providing a new growth accounting estimate of electricity's contribution to productivity growth in early twentieth century America. The estimate is that electricity raised the growth rate of labor productivity by an average of 0.54 percentage points over the period 1899-1929 – well above the 0.24 percentage points from steam in 1830-60 – with a sizeable contribution from TFP spillovers in the switch in the factory from shafts to wires. This exercise shows that the productivity gains from electricity actually came rather quickly compared with its predecessor technology, steam. Indeed the picture that emerges from Tables 2, 3, and 4 taken together is that the waiting time for a significant labor productivity payoff from the new GPT has fallen over time.

An alternative way to implement endogenous innovation growth accounting for the industrial revolution is to consider the 'modernized sectors' (cottons, woolens, iron, canals, ships, railways) as defined by Harley, who provides estimates of their contribution to TFP growth for the period 1780-1860 using gross output weights.[35] This would allow a rather broader view of the role played by GPTs in the British industrial revolution, in particular capturing the impact of the adoption of the factory system which, it has been argued, should be considered as a GPT.[36] At the same time, taking into account all these sectors will very largely subsume the contribution of steam including any TFP spillovers, although these will not be able to be measured separately. Capital stock data for the modernized sectors to supplement Harley's TFP growth estimates with capital-deepening contributions to labor productivity are reported in Table 5.

Table 6 displays the results of this new growth accounting exercise. The modernized sectors are found to have contributed 0.46 out of 0.78 per cent per year growth in labor productivity with the majority of this, 0.34 compared with 0.12 per cent, coming from TFP growth as opposed to capital deepening. If the contribution of technological change to the growth of labor productivity is taken to be capital deepening in the modernized sectors plus total TFP growth, then this equates to 0.68 out of 0.78 per cent.

ACCOUNTING FOR THE INDUSTRIAL REVOLUTION

In the light of these results, it is now appropriate to review the TFP growth paradox of the industrial revolution. The preceding section can help to clarify why famous technological breakthroughs had a relatively limited impact on productivity growth. The explicit account taken of the embodiment of new technologies in capital goods also leads to a somewhat revised estimate of the role of technological change in the growth outcomes of the period.

The evidence on the productivity impact of steam reveals both that it was slow to materialize and that, at least prior to 1860, it was weak by comparison with other GPTs usually spoken of in the same breath, electricity and ICT. The real price of steam power stayed high for many decades and, consequently, the build up of steam horsepower was very gradual with only 160,000 horsepower in use in 1830. At this time for most of the economy steam was irrelevant. Even in textiles, which came to predominate in the use of steam by the mid-nineteenth century, water power was cheaper in most of the industry until the 1830s.[37]TFP growth attributable to steam, even including railways, through to 1860 was much smaller than would later accrue from electricity or ICT at similar stages of their development.

Taken together with the confirmation of the dual estimates of Antras and Voth (reported in Table 1) that overall TFP growth was not fast enough to allow a substantial role for TFP growth in the rest of the economy beyond the modernized sectors and agriculture, the limited applicability of steam power in the classic industrial revolution period indicates that productivity growth did not take the form of a yeast like process.[38]

The social savings literature informed us a long time ago that even spectacular innovations like the railroad have small initial implications for growth. In a growth accounting context the fundamental reason for this becomes apparent. In the first phase of the new technology its output weight relative to GDP is so small that it cannot make a great deal of difference to overall TFP growth. If the capital-deepening contribution of embodied technological progress is also taken into account, this conclusion is modified somewhat but not overturned.

With traditional growth accounting, as in Table 1, TFP growth accounts for a little over a quarter of the growth of GDP between 1780 and 1860 (0.56/2.0 percentage points).[39]Taking the view that the contribution of the growth in the modernized sector's capital stock at 3.21 per cent per year in Table 5 should be added to this because it represents the embodiment of new technologies would raise the estimate of the contribution of technological change by (3.21 x 0.059) = 0.19 percentage points to a combined total of 0.75/2.0 = 37.5 per cent. This would still be well short of the share of about a half that was the basis of McCloskey's claim that "ingenuity rather than abstention governed the industrial revolution".[40]

This is not, however, the most informative way to look at growth during the industrial revolution. The great achievement of the British economy was to raise labor productivity (and sustain living standards) in the face of demographic pressure that in earlier centuries would have depressed output per worker. When traditional growth accounting is applied to the growth of labor productivity, Table 6 shows that between 1780 and 1860 TFP growth was responsible for over 70 percent (0.56/0.78 percentage points). If the embodiment hypothesis is added to this, then the contribution of technological change rises to 0.56 + 0.12 = 0.68 out of 0.78 percentage points, i. e., 87 per cent.

Or put another way, the increase in labor productivity growth after 1780 was a little under 0.5 percentage points per year compared with the period 1700 to 1780. This is much the same as the contribution of the modernized sectors according to Table 6. It remains perfectly feasible, therefore, to regard technological innovation as responsible for the acceleration in labor productivity growth that marked the importance of the industrial revolution as an historical discontinuity.

CONCLUSIONS

The method of growth accounting used by applied economists to examine contemporary productivity performance has changed. In the wake of the new growth theory, it seems appropriate to take explicit account of the embodiment of technological change in new varieties of capital goods. This approach meets a need frequently expressed by economic historians and appears quite suitable for analyzing the episode of the industrial revolution.

Moving from traditional to new growth accounting raises the estimated contribution of improvements in technology to British economic growth in the period 1780 to 1860 but not greatly. In terms of growth of GDP the estimated share of technological change rises from a little over a quarter to three-eighths while in terms of labor productivity the increase is from just over 70 per cent to seven-eighths.

Viewing the industrial revolution through the lens of the literature on General Purpose Technologies is also helpful. This predicts that the early years of a GPT will see little or no impact on aggregate productivity growth. In the industrial revolution the contribution of steam power to the macroeconomy amply bears out this prediction even when capital deepening is included along with TFP growth. Indeed, benchmarked in terms of other GPTs such as electricity and ICT, steam is seen to have had a relatively small and long-delayed effect on the growth rate of labor productivity. To a considerable extent, unspectacular productivity advance during the industrial revolution can be understood in terms of the rather weak impact of steam as a GPT.

This finding is not surprising when the results of early cliometricians' research into the social savings of steam-based innovations are recalled. However, it should be noted that whether the benchmark is set in terms of TFP growth alone (as it would be on the Fogel yardstick) or TFP growth and capital-deepening (as on the Oliner and Sichel measure) steam delivered much less, much later than either electricity or ICT.

Table 1. Accounting for Growth During the British Industrial Revolution (% per year)

		Contributions from		
	Output Growth	Capital Stock Growth	Labor Force Growth	TFP
Crafts				
1760-80	0.6	0.25	0.35	0.0
1780-1831	1.7	0.60	0.80	0.3
1831-73	2.4	0.90	0.75	0.75
Feinstein				
1761-1800	1.1	0.5	0.4	0.2
1801-30	2.7	0.7	0.7	1.3
1831-60	2.5	1.0	0.7	0.8
		Contributions from		
	Output Growth	Capital Stock Growth	Human Capital Stock Growth	TFP
Greasley & Oxley				
1760-80	0.6	0.3	0.2	0.1
1780-1831	1.7	0.6	1.1	0.0
1831-73	2.4	0.9	1.7	-0.2
	Contributions from			
	Capital Income	Labor Income	Land Income	TFP
Antras & Voth				
1770-1801	-0.1	0.2	0.0	0.1
1801-31	0.3	0.2	0.0	0.5
1831-60	0.3	0.3	0.0	0.6

Notes: weights: Crafts: capital 0.4, labor 0.6; Feinstein: capital 0.5, labor 0.5; Greasley and Oxley: capital 0.4, human capital 0.6; Antras and Voth: capital 0.35, labor 0.5, land 0.15.
Sources: Crafts, "Exogenous or Endogenous Growth," p. 752; Feinstein, "Capital Accumulation," p. 139, 141; Greasley and Oxley, "Endogenous Growth," p. 943; Antras and Voth, "Productivity Growth," p. 16.

Table 2. Contributions to Labor Productivity Growth in US Non-Farm Business Sector, 1974-99 (% per year)

	1974-90	1991-5	1996-9
Capital Deepening	0.81	0.62	1.10
ICT Capital	0.44	0.51	0.96
Other	0.37	0.11	0.14
Total Factor Productivity	0.33	0.48	1.16
ICT Sector	0.17	0.23	0.49
Other	0.16	0.25	0.67
Labor Quality	0.22	0.44	0.31
Labor Productivity Growth	1.37	1.53	2.57
Memorandum Items			
ICT Capital Income Share (%)	3.3	5.3	6.3
ICT Sector Output Share (%)	1.4	1.9	2.5

Source: derived from Oliner and Sichel, "Resurgence", p. 10, 13, and 17

Table 3. Steam's Contribution to British Labor Productivity Growth, 1760-1860 (% per year)

	1760-1800	1800-30	1830-60
Steam Engine Capital Stock Growth	4.3	3.9	4.9
Income Share (%)	0.1	0.2	0.7
Steam Power Capital Deepening	***0.004***	***0.008***	***0.03***
Steam Engine TFP Growth	6.7	0.0	3.4
Output Share (%)	0.04	0.1	0.3
Steam Power TFP	***0.003***	***0.00***	***0.01***
Railway Capital Stock Growth			16.2
Income Share (%)			0.9
Railway Capital Deepening			***0.15***
Railway TFP Growth			3.5
Output Share (%)			1.4
Railway TFP			***0.05***
Total Steam	***0.004***	***0.008***	***0.24***

Sources:
Steam power: capital stock growth proxied by horsepower, for 1760-1830 from Kanefsky, "Diffusion," p.338, for 1860 the average of estimates for 1850 in Musson, " Industrial Motive Power," p. 435, and for 1870 in Kanefsky, " Motive Power," p.373 with the 1850 estimate corrected in line with Kanefsky's criticisms; TFP growth in steam power based on von Tunzelmann, *Steam Power*, p. 74, 149-50 based on social savings of Watt engines for 1800 and subsequent trends in the real cost of steam power. Steam engine share assumed proportional to share of total capital stock in Feinstein, "National Statistics," p. 433 based on total capital costs of steam power in von Tunzelmann, *Steam Power* with 1835 estimate reduced by 20 per cent for 1860 based on Blaug, "Productivity," p. 372. Gross output shares for production of steam HP based on average additions to horsepower per year plus capital costs from von Tunzelmann, *Steam Power* and nominal GDP estimates from Deane and Cole, *British Economic Growth*, p.166.
Railways: growth of capital stock from Feinstein, "National Statistics," p. 448; TFP growth is average rate for 1840-60 from Hawke, *Railways*, p. 302; output and income shares based on gross and net earnings in Mitchell, *British Historical Statistics*, pp. 545-6 and national income in Deane and Cole, *British Economic Growth* p. 166 for period mid-point.
Labor force growth from Wrigley et al., *English Population History*, pp. 614-5 based on English population aged 15-64.

Table 4. Contributions to Labor Productivity Growth in US Private Non-Farm Domestic Economy, 1899-1929 (% per year)

Capital Deepening	0.34
Electrical Capital	0.24
Other	0.10
Total Factor Productivity	1.65
Electrical Sector	0.06
Electrical Capital Spillovers	0.24
Other	1.35
Labor Quality	0.16
Labor Productivity Growth	2.15
Memorandum Items	
Electrical Capital Income Share (%)	3.0
Electrical Sector Output Share (%)	1.7

Sources: aggregate economy data from Kendrick, *Productivity Trends*, pp. 338-9; growth rate of electrical capital goods in use proxied by growth of horsepower in electric drive in manufacturing in Devine, "From Shafts," p.351; electrical sector comprises electrical machinery and electric utilities for which capital stock growth and TFP growth are from Kendrick, *Productivity Trends*, p.475, 590-1; electrical capital spillovers based on David and Wright, "Early Twentieth Century," p.41, see text; electrical capital goods income share based on Bureau of Economic Analysis, *Fixed Non-Residential Business Capital*, p. 158 and Gould, *Output*, p.28, 61, 65; electrical sector output share derived from Fabricant, *Output*, pp. 628-9 and Gould, *Output* p. 28, 47, 163.

Table 5. Modernized Sector Capital Stock, 1780 and 1860. (£mn, 1851-60 prices)

	1780	1860
Cotton Textiles	1.9	46
Woolen Textiles	7.4	13
Iron	1.1	44
Canals	12	37
Ships	14	65
Railways	0	253
Total	36.4	458

Sources:
1780: cotton textiles from Chapman and Butt, "Cotton Industry," p. 109; woolen textiles from Jenkins, "Wool Textile Industry," p. 134; iron based on cumulated investment since 1750 from Davies and Pollard "Iron Industry," p. 102; canals based on Feinstein, "Capital Formation," p. 42, adjusted to 1780 using Ginarlis and Pollard, "Roads," p. 217; ships from Feinstein, "National Statistics," p. 450.
1860: cotton and woolen textiles from Feinstein, "Capital Formation," p. 53; iron based on cumulated investment from Davies and Pollard, "Iron Industry," p. 102; canals from Feinstein, "Capital Formation," p. 42, ships from Feinstein, "National Statistics," p. 450; railways from Feinstein, "National Statistics," p. 448.
Where required, estimates in nominal prices deflated using capital goods price index from Feinstein, "Capital Formation," p. 38.

Table 6. Contributions to British Labor Productivity Growth, 1780-1860 (% per year)

Capital Deepening	0.22
Modernized Sectors	0.12
Other	0.10
Total Factor Productivity	0.56
Modernized Sectors	0.34
Other	0.22
Labor Productivity Growth	0.78
Memorandum Items	
Labor Force Growth	1.22
Capital Income Share (%)	40
Modernized	5.9

Sources:
Total capital stock growth from Feinstein, "National Statistics," p.448; modernized sector capital stock from Table 3, labor force growth from Table 2.
TFP growth using output growth as in Crafts, "Exogenous or Endogenous Growth," p.752; modernized sector TFP growth from Harley, "Reassessing," p.184.

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Endnotes

[1] This has been set out successively in Crafts, "English Economic Growth", idem, "National Income Estimates", Harley, "British Industrialization", Crafts, *British Economic Growth,* Crafts and Harley, "Output Growth", Harley, "Reassessing" and Harley and Crafts, "Simulating". For dissenting views see Temin, "Two Views", and Berg and Hudson, "Rehabilitating".

[2] Mokyr, "Editor's Introduction", p. 25.

[3] Harley, "Reassessing", p. 184.

[4] The best introduction to which is the edited collection of essays in Helpman, *General Purpose Technologies*.

[5] Lipsey et al., "What Requires Explanation?"

[6] Von Tunzelmann, *Steam Power*, p. 149.

[7] Hawke, *Railways*, p. 406; Deane and Cole, *British Economic Growth*, p. 166.

[8] David and Wright, "Early Twentieth Century".

[9] Greasley and Oxley, "Endogenous Growth", p. 937.

[10] Crafts and Mills, "Endogenous Innovation".

[11] Mitch, "Role of Education", p. 255.

[12] Barro, "Notes".

[13] Feinstein, "Capital Accumulation", p. 142.

[14] Jorgenson and Stiroh, "Raising the Speed Limit", Oliner and Sichel, "Resurgence", US Council of Economic Advisers, *Economic Report*.

[15] Barro and Sala-i-Martin, *Economic Growth*, ch. 6.

[16] Oliner and Sichel, "Resurgence".

[17] This is the tradition deriving from Romer, "Increasing Returns".

[18] See, for example, Pilat and Lee, "Productivity Growth", and Stiroh, "Information Technology".

[19] Fishlow, *American Railroads*; Fogel, *Railroads*.

[20] Jara-Diaz, "On the Relation".

[21] Fogel, "Notes", p. 3.

[22] Harberger, "Vision".

[23] Foreman-Peck, "Railways"; Hawke, *Railways*.

[24] Kanefsky, "Diffusion", p. 338; idem, "Motive Power", p. 373.

[25] Idem, "Diffusion", pp. 145-6.

[26] Ibid., pp. 175-6.

[27] von Tunzelmann, *Steam Power*, pp. 72-4.

[28] Ibid., p.150.

[29] Hedonic pricing is not responsible for very much of the gap between the growth contributions of steam in table 3 and ICT in Table 2. A crude estimate of its impact can be obtained by comparing the rates of price decrease for computers and software according to the national accounts of the USA and of the UK, a country which continued to use traditional methods to estimate price declines for these items. The data presented in Oulton, "ICT and Productivity" show that price decreases in the United States for computers (software) were greater by 7.3 (0.6) per cent per year for 1979-89 and 8.8 (3.4) per cent per year for 1989-94. This suggests that the use of hedonic prices in Table 2 raises the ICT capital-deepening contribution by a little less than 0.1 percentage points per year and the own TFP contribution by a similar amount. If a correction of this magnitude were made, then the impact of ICT on growth prior to 1995 would still far outstrip steam.

[30] Hawke, *Railways*, pp. 381-400.

[31] von Tunzelmann, *Steam Power*, p. 183, 292.

[32] Musson, "Industrial Motive Power", p. 436; Crafts and Venables, "Globalization in History".

[33] Hawke, *Railways*; von Tunzelmann, *Steam Power*.

[34] David, "Computer and Dynamo".

[35] Harley, "Reassessing", p. 184.

[36] Lipsey et al., "What Requires Explanation?", p. 45.

[37] Chapman, "Cost of Power".

[38] This terminology was introduced by Harberger, "Vision"; the metaphor that he proposed for local as opposed to general advance is mushrooms rather than yeast.

[39] Using the data and assumptions in Crafts "Exogenous or Endogenous Growth".

[40] McCloskey, "Industrial Revolution", p. 108; using the estimate of TFP growth at 1.2 per cent per year in Table 6.2 of that paper and growth at 2.5 per cent per year as implied by Deane and Cole's estimates for 1780-1860.