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Quantifying the Contribution of Technological Change to Economic Growth in Different Eras: A Review of the Evidence

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> *"Our knowledge of economic history, of what production looked like 100 years ago, and of current events convinces us beyond any doubt that discovery, invention, and innovation are of overwhelming importance in economic growth... we could produce statistical evidence suggesting that all growth came from capital accumulation with no room for anything called technological change but we would not believe it"*
> (Romer, 1993, p. 562)

1. Introduction

Most economic historians would surely endorse Paul Romer's view expressed above that technological progress lies at the heart of long run economic growth. Long ago Kuznets identified the epoch of 'modern economic growth' as one where growth came to be driven by scientific and technological advance. And indeed, the experience of the first industrial revolution itself has been viewed as the triumph of "ingenuity rather than abstention" (McCloskey, 1981, p. 108).

The standard way of justifying a claim of this kind would be to appeal to growth accounting estimates. The traditional neoclassical methodology captures a contribution to growth from exogenous technological change in the Solow residual estimate of total factor productivity (TFP) growth. With the standard Cobb-Douglas production function

$$Y = AK^{\alpha}L^{\beta} \qquad (1)$$

the Solow residual is computed as

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

where s_K and s_L are the factor income shares of capital and labour respectively.

Equation (2) can be converted into an expression that accounts for the rate of growth of labour productivity as follows:

$$\Delta(Y/L)/(Y/L) = s_K \Delta(K/L)/(K/L) + \Delta A/A \tag{3}$$

When this formula was first proposed the startling claim that arose was that over eight decades a very high proportion, perhaps 90 per cent of labour productivity growth came from the residual (Abramovitz, 1956). But was this really the contribution of technological change or a statistical artefact or the 'measure of our ignorance' of the sources of economic growth? Abramovitz himself raised these issues and Jorgenson and Griliches (1967) argued that, properly measured, virtually all recent American economic growth was attributable to the growth of conventional capital and labour inputs.

Yet, at other times, economists have puzzled that in the face of dramatic technological change there seems to be little reflection of this in the growth accounting estimates. The best-known example of this is the so-called Solow Productivity Paradox coined in 1987 that "You can see the computer age everywhere but in the productivity statistics". But similar issues arise in the context of the British industrial revolution where it is now generally accepted that TFP growth was quite modest (Antras and Voth, 2003) and in the context of the contribution of the railroads to economic growth where Fogel's famous conclusion was that the social savings from freight transport were no more than 4.7 per cent of 1890 GNP and that, contrary to conventional wisdom, "no single innovation was vital for economic growth in the nineteenth century" (1964, p. 234).

Since the early days of growth accounting there have been several important developments. First, there is now a wide array of historical national accounts and a great many growth accounting exercises have been carried out such that a much broader historical perspective is now possible. Second, better measurement of the key aggregates is now feasible in terms of taking into account changes in the quality of inputs and a number of cross-checks have been developed that can be used to assess the plausibility of estimates of TFP growth. Third, the theory of growth accounting and its relationship to growth economics is better developed so that the distinction between TFP growth and underlying technological change is now much clearer.

It seems opportune therefore to review what quantitative economic history now has to say about the contribution of technological change to economic growth. This may be useful not only for economic historians but also for economists given that the time series evidence that economic history alone can provide is a key ingredient for the assessment of a number of claims in the endogenous growth literature. Accordingly, the following questions will be addressed.

(1) Based on traditional growth accounting, how big a contribution to labour productivity growth has resulted from TFP growth ?

(2) Accepting traditional neoclassical methods, are the resulting TFP growth estimates a reliable guide to the contribution of technological change to productivity advance?

(3) Does new growth economics imply revisions to the traditional results ?

(4) Can we resolve the rapid technological change, slow TFP growth paradox?

2. A Flavour of Standard Growth Accounting Results

In this section conventional growth accounting estimates of the contribution of TFP growth to labour productivity growth are presented. Obviously, no more than a sample of results in the literature can be provided. Table 1 displays a selection of results which relate to different time periods and a spread of regions including developing as well as developed countries. The growth accounting reported in Table 1 makes no allowance for changes in the quality of factors of production and in today's terminology might be thought of as 'crude TFP' estimates.

Taking these 'crude TFP' estimates at face value several points are apparent. First, it is clear that TFP has not always accounted for virtually the whole of labour productivity growth, even in the United States. While for the years 1890-1966, the proportion is 75 per cent or more, it was much lower before 1890 and fell off sharply after 1966. A similar picture emerges for most other OECD countries for which estimates exist, namely, that the importance of TFP growth seems to peak in the third quarter of the twentieth century and then fall back (Maddison, 1991).

Second, the absolute value of TFP growth in the twentieth century has far exceeded that of the nineteenth century. Indeed, a striking feature of these estimates is that crude TFP growth was less than 0.5 per cent per year until after the Civil War in the United States (Abramovitz, 1993) and also during the classic industrial revolution period in Britain.

Third, the proportion of labour productivity growth accounted for by TFP has been distinctly lower in recent cases of rapid catch-up growth in which the role of capital deepening tends to be important. In east Asia as a whole capital deepening accounted for 60 per cent of labour productivity growth during 1960-1994 and both Korea and Singapore were near this fraction.

The most common correction to these crude estimates, especially since Denison (1967), is to make an adjustment for the impact of education on labour inputs based on the increment to earnings (and thus 'person power') of an extra year's schooling. Despite some theoretical doubts, recent research suggests that this is generally a reasonable procedure (Kreuger and Lindahl, 2000; Cohen and Soto, 2001).

If this adjustment is made, then the contribution of TFP growth is reduced by an equivalent amount. Generally speaking, this magnitude is of the order of 0.4 to 0.5 per cent in OECD countries in the post-1950 period but virtually zero in early nineteenth century UK and USA. Obviously, this reduces the apparent difference in the rate of technological progress between the nineteenth and twentieth centuries but nevertheless the gap is still large.

Subtracting the contribution of extra schooling from crude TFP accentuates the finding that catch-up growth in east Asia has owed relatively little to TFP. The adjusted TFP growth estimate is only a little higher than in south Asia (1.1 compared with 0.9 per cent per year) and the proportion of labour productivity growth due to TFP growth is only 26 per cent, about half that of West Germany during the European Golden Age.

3. Does Measured TFP Growth Capture the Contribution of Technological Change to Labour Productivity Growth ?

There are many reasons why in practice measured TFP growth should not be interpreted as an estimate of the contribution of technological progress to labour productivity growth even if the basic neoclassical framework is retained. The discrepancy can arise from measurement error, from imposing inappropriate assumptions about the specification of the production function, or from improvements in the efficiency with which resources are allocated. These problems can result in either upward or downward bias.

3.1 Resource allocation effects

Some writers have attempted to identify various sources of TFP growth. Table 2 displays the results of an exercise of this kind carried out by Maddison (1991) (1996). The components labelled 'structural' and 'foreign trade' represent resource allocation effects while the 'scale' component is occasioned by correcting the standard constant returns to scale assumption of the neoclassical production function. Technological progress based on diffusion (technology transfer) is captured by the 'catch-up' component. 'Unexplained' is self-explanatory but presumably includes better technology. An upper-bound estimate of the share of TFP that is accounted for by technological progress is therefore the sum of the 'catch-up' and 'unexplained' components. It should be noted that Maddison's decomposition of TFP is rather ad hoc and could be regarded as contentious in some respects; for example, the impact of structural changes in employment has been estimated quite differently by Broadberry (1998). Nevertheless, the main messages of Table 2 are probably reasonably robust.

Maddison himself argues that when growth accounting is approached this way the proportion of growth that remains unexplained is quite small and that it may be possible to reduce this fraction further. The implication of this is that the share of labour productivity growth accounted for by technological change is much smaller than might have been supposed in the early days of growth accounting. Taking the upper bound from the estimates from Table 2, it is almost always less than 50 per cent and averages less than 30 per cent.

It should be noted that the other components of TFP growth have a variable impact over time and, in particular, were quite strong during the Golden Age. This does not undermine the proposition that the impact of technological change on productivity growth was at its peak in this period but it does mean that comparisons between periods should not be based on crude TFP. Moreover, it is clearly wrong to interpret fast TFP growth in countries experiencing rapid catch-up growth simply as a result of technology transfer.

3.2 Using factor shares as proxies for output elasticities

The usual way to implement growth accounting weights the rates of growth of the factors of production by their factor income shares. This can be justified by an appeal to competitive factor markets in which factors receive rewards equal to their marginal productivity. The contribution to growth of each factor of production is based on the elasticity of output with respect to it.

$$\Delta Y = (\Delta K \times MPK) + (\Delta L \times MPL) + \Delta A \quad (4)$$

so

$$\Delta Y/Y = (\Delta K/K)(MPK \times K)/Y + (\Delta L/L)(MPL \times L)/Y + \Delta A/A \quad (5)$$

where (MPK x K)/Y and (MPL x L)/Y will be the shares of profits and wages, s_K and s_L, in income under neoclassical assumptions.

There are at least three potentially serious problems, however. First, if there is market power resulting in supernormal profits, then s_K will be an overestimate of the output elasticity and the contribution of capital will be overestimated and that of TFP growth underestimated. Second, if there are externalities such that the social rate of return to investment exceeds the private rate, then s_K underestimates the output elasticity and TFP growth is overestimated. Third, self-employment produces a major headache since the income of the self-employed has to be divided into capital and labour shares.

As a result most comparative studies which have attempted to benchmark productivity performance across countries have imposed constant factor shares, typically with $s_K = 0.3$ or 0.35. This is fairly close to the share of profits, at least in OECD countries, and attempts to estimate the elasticity of output with respect to capital using econometric techniques suggest that this is an acceptable procedure (Cohen and Soto, 2001) (Oulton and Young, 1996). Thus the potential problems of using factor income share weights are perhaps not very serious after all.

3.3 Biased technological change and the elasticity of substitution between factors

The standard growth accounting approach is valid providing that there are constant returns to scale, the elasticity of substitution between factors of production equals 1, and technological progress is Hicks-neutral, i.e., if the production function is Cobb-Douglas. In fact these conditions may not apply; in particular, it has been argued that both in the United States in the nineteenth century (Abramovitz, 1993) and also in east Asia in recent decades (Rodrik, 1997) it is likely that the elasticity of substitution was less than 1 and technological progress was Hicks labour saving. Thus the extent to which technological progress in the twentieth century United States exceeded that of the nineteenth would be exaggerated by conventional assumptions as would the contribution of accumulation relative to the assimilation of new technology in east Asia.

In such circumstances applying the standard assumptions will lead to a downward bias in the estimated rate of TFP growth (and of technological progress) which will increase with the rate of capital deepening, the degree of labour saving bias and the inelasticity of substitution. Taking a fairly extreme assumption that the elasticity of substitution was as low as 0.6 would imply that the downward bias in east Asian TFP growth in 1960-94 in Table 1 would be about 0.8 per cent per year and that for the United States in 1855-90 about 0.25 per cent per year. This would certainly modify the conclusions drawn earlier about the proportion of labour productivity growth due to technological progress but would still leave the east Asian share below 50 per cent and would still imply that technological change in the mid twentieth century was well above that of the mid nineteenth century in the United States.

3.4 Fixed factors and adjustment costs

Technological progress results in a shift of the long run average cost curve (LRAC) and in long run equilibrium would be measured by the fall in the lowest point of LRAC where there is competitive long run equilibrium and optimal capacity working. But to be at this point assumes full adjustment of factors of production that are fixed in the short term so observed costs may not be points on LRAC. Moreover, there will be lags in reaching optimal capacity if in the short term the supply curve of capital goods is inelastic such that there are adjustment costs of investment.

Morrison (1993) drew attention to the importance of these issues in estimating the true rate of technological progress and proposed a way of adjusting TFP for adjustment costs, fixed factors, and also economies of scale. Her method has been little used probably because it is data demanding and is based on an econometric technique that is difficult to implement satisfactorily. Her own results suggested that the manufacturing productivity slowdown in the United States in the 1970s was very largely a result of a weakening of economies of scale rather than of technological progress.

Two papers that have used this approach in economic history are by Rossi and Toniolo (1996) and Crafts and Mills (2001). The former found that a substantial fraction (about two-fifths) of Italian TFP growth in the Golden Age was from economies of scale and that only a third was from technological change. If this also applied to other cases of rapid postwar catch-up growth like France and Germany, then a much bigger correction than that made by Maddison (1996), and reported in Table 2, would be warranted.

By contrast, the latter paper which looked at UK and German manufacturing found little role for economies of scale but a large one for adjustment costs. In fact, Crafts and Mills (2001) estimated that technological change was about 2 percentage points faster than TFP growth in both countries during 1950-73. These results when combined with those of Morrison (1993) indicate that the rate of technological catch-up by the UK and Germany of American manufacturing during the Golden Age was much faster than crude TFP estimates suggest.

Several implications follow. First, it seems important that more studies using the Morrison methodology are undertaken since the size of the biases uncovered thus far are substantial. Second, it seems likely that interpreting TFP growth in the Golden Age is particularly difficult in an era when European economies were liberalizing, exploiting Fordist technology and exposed to shortages of capital goods in a non-globalized world. Third, there are further reasons to be sceptical that the pattern of TFP growth in economies over time is closely related to that of technological change.

3.5 Price indices and output growth

TFP growth is the difference between the rate of real output growth and the rate of total factor input growth. The measurement of output growth is therefore a central concern in obtaining TFP growth estimates. Typically, at the level of GDP, real output growth is measured by deflating estimates of output in current prices by an appropriate price index. This sounds straightforward but adjustment to constant prices has not always been implemented well. For example, virtually all the difference between the Crafts-Harley estimates of productivity growth during the industrial revolution and their predecessors is attributable to the ways in which this index number problem was addressed.

Contemporary economists have discovered this issue in the context of the post-Golden Age productivity slowdown, especially in the United States where the problem was famously examined by Boskin et al. (1996). The problem is partly the rise of 'hard to measure' components of GDP, especially in the service sectors and durable goods production, where quality change is important. The Boskin Commission report thought that this might lead to an underestimate of real output growth of the order of 0.6 per year in recent times.

It should be noted that this kind of problem need not always have a big impact in measuring TFP growth and does not always imply that TFP growth is underestimated because it may affect both input and output growth. A case in point is the information and communications technology (ICT) revolution where adjusting for quality change in computers and software has a roughly offsetting impact on measured TFP growth in the UK for the period 1989-98 such that while GDP growth was underestimated by conventional methods by 0.3 percentage points per year, TFP growth was overestimated by 0.1 percentage points (Oulton, 2002).

For economic historians, however, the issue is more serious because they typically wish to know how much technological change has contributed to improving living standards, i.e., they would like to have available a welfare as well as a production interpretation of productivity growth. In this context, the appropriate index with which to adjust nominal output is a cost of living index (COLI) not a fixed basket cost of goods index (COGI). A COLI measures the change in expenditures that a person would have to make in order to maintain a given standard of living, i.e, to stay on a given indifference curve.

This entails taking account of substitution biases (switching consumption to now cheaper goods) and the consumer surplus gains arising from new characteristics embodied in product innovations. This may be substantial, for example, a recent estimate for mobile phones in the United States was $111 billion in 1999 (Hausman, 2003). According to recent research by Costa (2001) which uses Engel curve relationships between expenditures on key categories of goods and income based on budget survey data, substitution biases in the American CPI have varied considerably over time and have, on occasion, been very large as Table 3 reports.

3.6 The role of dual estimates of TFP

Finally, it is useful to consider the role that dual methods of estimating TFP growth can have as reality checks on the results of orthodox (primal) methods of growth accounting. Two alternative growth accounting formulae which are exactly equivalent to the traditional Solow method are available.

First, the relationship between TFP growth and the rate of growth of factor prices can be exploited (Barro, 1999). Starting from a definition of income as

$$Y = rK + wL \quad (6)$$

then

$$\Delta Y/Y = s_K(\Delta r/r + \Delta K/K) + s_L(\Delta w/w + \Delta L/L) \quad (7)$$

so

$$\Delta A/A = \Delta Y/Y - s_K\Delta K/K - s_L\Delta L/L = s_K\Delta r/r + s_L\Delta w/w \quad (8)$$

that is, the rate of TFP growth is equal to factor-share-weighted average of the rate of growth of the real rental rate of capital and real wage growth.

In practice, this tells us that, unless real wages are growing appreciably, it is unlikely that TFP growth is rapid. Antras and Voth (2003) have exploited this formula as an independent check on the Crafts and Harley (1992) claim that TFP growth during the British industrial revolution, famous for its 'wave of gadgets', was much less rapid than was once believed. Not surprisingly, since the period is known for the very slow growth of real wages they conclude that TFP growth was indeed modest during the period 1780-1830 and their estimate is similar to that of Crafts and Harley.

Second, the relationship between the price of output and input prices can be used. Thus, the equivalent to the traditional Solow formula is

$$\Delta A/A = s_K\Delta r/r + s_L\Delta w/w - \Delta p/p \quad (9)$$

This may not be very helpful at the macroeconomic level because of problems in accurately measuring the rate of price change discussed above. But it is important as a way of establishing the presence of rapid technological change at the micro level.

If the Solow residual really does reflect technological change, then we would expect sectors in which this is happening to experience rapid declines in output prices as was the case with cotton yarn in the 1780s and computers in the 1990s. In the latter case the ability to document in this way rapid TFP growth in ICT production was central to establishing that the upturn in TFP in the United States in the mid-1990s was not simply a business cycle phenomenon (Oliner and Sichel, 2000).

3.7 In sum

The answer to the question posed at the start of this section regrettably is "no". It is clear that there are frequently quite sizable differences between the underlying rate of technological change and measured TFP growth. Moreover, it seems clear that these may vary greatly over time such that comparisons of TFP growth between periods can be quite misleading. For example, TFP growth exceeded technological change in Golden Age Europe but the opposite was the case in the United States in both the late nineteenth and late twentieth centuries. Cross-sectional comparisons of TFP growth between countries at a similar stage of development are probably more informative.

4. What are the Implications of Endogenous Innovation ?

Growth accounting as it developed in the 1950s was closely linked to permutations of the Solow growth model. In the 1980s and early 1990s this was challenged and, in some ways, superseded by new growth economics, notably by models that embodied the hypothesis of endogenous innovation. Adopting such a model has implications for identifying the contribution of technological change in a growth accounting framework.

For example, consider the model proposed in Barro (1999) in which

$$Y = AL^{1-\alpha} N^{1-\alpha} K^{\alpha} \tag{10}$$

where K = Nk which is the input of the aggregate capital stock which is made up of N varieties and k_j is the input of the jth type of capital good. This equation says that diminishing returns set in when K increases for given N but not when N rises for given K. There is a basis for endogenous growth through technological progress in the form of increases in N over time.

The formula for TFP growth based on this production function can be written as

$$\Delta A/A = \Delta Y/Y - s_K \Delta K/K - s_L \Delta L/L = \Delta A/A + (1-\alpha)\Delta N/N \tag{11}$$

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 generalization of this approach to allow for the embodiment of new technology in capital goods has been adopted by practitioners in the literature on the growth effects of ICT. Thus Oliner and Sichel (2000) identified the contribution of innovations in ICT to the growth of labour 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. Thus equation (3) becomes

$$\Delta(Y/L)/(Y/L) = s_{KO}\Delta(K_O/L)/(K_O/L) + s_{Ki}\Delta(K_i/L)/(K_i/L) + \gamma(\Delta A/A)_{ICTM} + \phi(\Delta A/A)_{NICTM} \quad (12)$$

where the subscript $_O$ indicates other capital, the subscript $_{Ki}$ indicates ICT capital of type i, the subscripts $_{ICTM}$ and $_{NICTM}$ indicate manufacture of ICT equipment and the rest of the economy, respectively, and γ and ϕ are the gross output shares of these sectors. Thus the innovation of ICT is allowed to have impacts on labour productivity growth both through an embodied capital-deepening effect as well as through orthodox TFP growth.

It should be noted that this type of growth accounting addresses the question 'how much did the new technology contribute ?' rather than the (much harder) question 'how much more did this technology contribute than an alternative investment might have yielded ?' The upper bound assumption is that, in the absence of the innovation, the economy would both have had 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.

New economic historians traditionally measured the contribution of a new technology to economic growth using the concept of social savings which was pioneered by Fogel (1964) in his study of the contribution made by railroads to nineteenth century American economic growth. This was computed as an upper bound measure of the gain in consumer surplus from the reduction in costs allowed by the new technology

$$SS = (p_w - p_R)q_R \quad (13)$$

where SS is social saving, p_W and p_R are the prices charged for water (the best alternative) and rail transport and q_R is the volume transport ed rail in the year of observation.

If demand is not perfectly 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 (Jara-Diaz, 1986). This is the interpretation that Fogel gave the social saving (1979, p. 3).

The price dual measure confirms that the fall over time in the real cost of rail transport is also equal to TFP growth so the social saving measure (expressed as a per annum addition to productive potential) 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 used to compute the estimate. Indeed, this equivalence is exactly how Foreman-Peck (1991) extended the social savings estimate for British railways to 1890. The social saving approach is equivalent to taking only the TFP and not the embodied capital contribution of an innovation; thus it is equivalent to neoclassical rather than endogenous-innovation-based growth accounting.

The logic of the social saving approach is quite clear in terms of Fogel's search for the unique 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.

It seems likely that many economists would instinctively believe in models that would imply answers somewhere between these two. Some would consider 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 at least some old capital goods that otherwise would have survived. Thus, it is useful to have both standards of comparison.

5. The Impact of New General Purpose Technologies on Productivity Growth

A General Purpose Technology (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" (Lipsey, et al., 1998). Electricity, steam and ICT are usually seen as among the most important examples. A key theme of recent models, perhaps provoked by the Solow Paradox, is that the initial impact of a GPT on productivity may be negligible or even negative. This might involve lags in understanding its full implications and learning how to exploit the GPT's potential or an element of disruption as the economy switches to the new technology and is reorganized.

Clearly, it is to be expected that a new GPT will have a substantial positive impact on the rate of labour productivity and TFP growth ... but how long will this take to materialize ? ... and will it dominate other aspects of productivity growth ? Exploring these issues is an excellent opportunity to use growth accounting with embodiment of new technology in capital goods and to compare the results with those obtained using the traditional neoclassical/social savings methodology.

5.1 ICT

Table 4 summarizes the results for ICT reported by Oliner and Sichel (2002) in an update of their well-known paper (Oliner and Sichel, 2000). Several points deserve to be highlighted. First, the total contribution of ICT including both capital-deepening and TFP growth in ICT production rises from 0.68 per cent in 1974-90 to 1.79 per cent per year after 1995. This is associated with rising shares of ICT capital income and ICT output. Second, although rates of TFP growth in ICT production were spectacular as Moore's Law held sway and rates of growth of the ICT capital stock were very rapid, these growth rates initially had a relatively modest impact on overall labour productivity growth because ICT was small relative to the economy as a whole. Third, there is a similar acceleration in the TFP contribution over time, from 0.27 per cent per year in 1974-90 to 0.77 per cent per year after 1995 but throughout the impact of ICT including the embodiment component is more than double that based on the social saving approach.

The impact of ICT by the late 1990s may in fact be larger than these estimates recognize. It is possible that in addition to the direct effects of ICT on TFP there were also spillovers just as it is thought that electricity promoted productivity-enhancing redesign of factories in the 1920s (David and Wright, 1999). The tendency for TFP growth in the United States to be concentrated in ICT-intensive sectors in the 1990s but not in the 1980s may reflect similar impacts (Stiroh, 2002).

There is also some evidence that the preoccupations of the theoretical GPT literature are valid in that there is evidence that obtaining significant labour productivity payoffs from ICT typically involves significant lags (Brynjolfsson and Hitt, 2000) and that TFP growth in ICT-using sectors is negatively related to contemporaneous ICT investment but positively related to past ICT investment with quite a long lag (Basu et al., 2003). It seems that substantial learning and reorganization inside firms has been required to realize the productivity payoffs from ICT.

5.2 Steam

Table 5 reports estimates from a similar growth accounting study for steam during the British industrial revolution. This produced the following important results. First, although James Watt's steam engine was invented in 1769, the impact of steam power on productivity growth prior to 1830, or indeed 1850 if the social saving approach is preferred, was tiny. Second, the largest impact of steam was in the period 1850-70 but this was much less than that of ICT in the late twentieth century United States. Third, here too the income and output shares of steam and thus the weights attached to steam capital deepening and TFP growth, are small initially. However, it is clear that there was no equivalent of Moore's Law during the steam era of the nineteenth century. Fourth, again including the embodied capital-deepening component at least doubles steam's contribution to labour productivity growth throughout.

Once the connection between the social savings approach and growth accounting is appreciated, these results should not be a surprise because they were largely anticipated by early cliometricians. Von Tunzelmann (1978) estimated that if the Watt steam engine had not been invented, the national income of Britain in 1800 would have been reduced by only about 0.1 per cent. Similarly, Hawke (1970) found that the social savings of railways in England and Wales in 1850 amounted to £9.7 million when British gross domestic product was £523 million.

The long delay in obtaining significant productivity growth based on steam power probably did not result from difficulties of reorganization but simply the high cost of early steam power. Not until high-pressure steam engines came into general use after 1850 was the full potential of the technology realised. As with ICT, the issue of TFP spillovers has not been fully resolved. Hawke (1970) and Von Tunzelmann (1978) both argued that these were unimportant in the first half of the eighteenth century, the former because canals had determined location decisions and the latter because textile technologies were designed for water power. Whether there were important TFP spillovers in the second half of the nineteenth century remains to be investigated.

5.3 In sum

A growth accounting perspective makes excellent sense of the apparent paradox of major technological changes co-existing with modest TFP and labour productivity growth. New technologies inevitably have small weights initially in any growth accounting procedure and it takes quite a long time before they become large enough to have a major impact. In fact, ICT appears to have had a strong effect on growth relatively quickly, although this may not appear so to those without an historical perspective. The lag before a GPT has its full effect on productivity is measured in decades not years.

These results also help explain the pattern of TFP growth that Britain experienced during the industrial revolution. Steam was in its infancy as a GPT and, had there been a general appreciation of the TFP growth implications of the social savings calculations of Hawke and von Tunzelmann there might have been much less surprise that careful investigation of aggregate TFP growth shows it was quite modest until the second quarter of the nineteenth century.

6. Conclusions

A formidable array of historical growth accounting studies have been conducted and the conventional methodology is firmly established as a valuable diagnostic tool. A number of important lessons have become apparent but new research issues have also emerged.

Two main messages should be heeded. First, the estimate of TFP growth that results from standard growth accounting is not necessarily a good indicator of the contribution made by technological change to economic growth. The discrepancy can go either way and has varied considerably both over time and also across countries. Second, even the most powerful new technologies have modest impacts on productivity growth in their early stages. This is easily understood in the context of growth accounting which makes explicit the weights to be attached to new types of capital and production.

Two main research needs have also been identified. First, attention needs to be paid to developments in growth economics that potentially imply the need for revised methods of growth accounting. The main issues concern the embodiment of new technology in capital goods rather than externalities to physical and human capital accumulation. Second, more serious attention needs to be given to the specification of the assumed production function and, especially, the role of scale economies. This suggests that economic historians may need to turn more to econometric methods in future rather than imposing Cobb-Douglas production function assumptions on the data.

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Tables

Table 1. Contribution of TFP to Labour Productivity Growth (% per year)

	Crude TFP	**Education**	**Labour Productivity**
USA			
1800-1855	0.2	0.0	0.4
1855-90	0.4	0.1	1.4
1890-1927	1.5	0.2	2.0
1929-66	2.1	0.4	2.5
1966-89	0.7	0.3	1.2
UK			
1780-1831	0.3	0.0	0.4
1831-73	0.8	0.3	1.2
1873-1913	0.5	0.3	0.9
1913-50	0.7	0.3	1.6
1950-73	1.4	0.2	3.1
1973-92	1.1	0.4	2.0
1950-73			
France	3.4	0.4	5.0
West Germany	3.5	0.2	6.0
Japan	4.1	0.5	7.4
1973-92			
France	1.3	0.7	2.6
West Germany	1.6	0.1	2.6
Japan	1.5	0.5	3.3
1960-1994			
East Asia	1.7	0.6	4.2
South Asia	1.2	0.3	2.3
Africa	–0.5	0.2	0.3
Latin America	0.6	0.4	1.5

Sources: USA: Abramovitz and David (1999); UK: 1780-1913: Crafts (2004); 1913-92: Maddison (1996); France, West Germany & Japan: Maddison (1996); Africa, Asia, Latin America: Collins and Bosworth (1996).

Table 2. Decomposing TFP Growth (% per year)

	France	Germany	Japan	UK
1913-1950				
GDP/Hour Worked	1.91	1.04	2.61	1.57
Total Factor Productivity	0.67	0.28	0.67	0.35
Catch-Up Effect	0.00	0.00	0.00	0.00
Foreign Trade Effect	0.03	-0.13	0.05	0.01
Structural Effect	0.04	0.20	0.40	-0.04
Scale Effect	0.03	0.04	0.07	0.04
Unexplained	0.57	0.17	0.15	0.34
Per cent unexplained	30	16	6	22
1950-1973				
GDP/Hour Worked	5.01	5.99	7.36	3.07
Total Factor Productivity	3.06	3.28	3.62	1.25
Catch-Up Effect	0.46	0.62	0.98	0.08
Foreign Trade Effect	0.37	0.48	0.53	0.32
Structural Effect	0.36	0.36	1.22	0.10
Scale Effect	0.15	0.18	0.28	0.09
Unexplained	1.72	1.64	0.61	0.66
Per cent unexplained	34	27	8	21
1973-1992				
GDP/Hour Worked	2.58	2.57	3.33	1.99
Total Factor Productivity	0.65	1.53	1.21	0.63
Catch-Up Effect	0.31	0.31	0.39	0.20
Foreign Trade Effect	0.12	0.15	0.09	0.15
Structural Effect	0.15	0.17	0.20	-0.09
Scale Effect	0.07	0.07	0.11	0.05
Unexplained	0.00	0.83	0.42	0.32
Per cent unexplained	0	32	13	16

Sources: derived from Maddison (1991) (1996). NB: TFP is a 'refined' masure, i.e., education is taken out and accounted for in factor input growth

Table 3. CPI Bias in the United States (% per year)

1888/90-1917/19	−0.1
1917/19-1935/6	0.7
1960-72	0.4
1972-82	2.7
1982-94	0.6

Source: Costa (2001).

Table 4. Contributions to Labour Productivity Growth in US Non-Farm Business Sector, 1974-2001 (% per year)

	1974-90	**1991-5**	**1996-2001**
Capital Deepening	0.77	0.52	1.19
ICT Capital	0.41	0.46	1.02
Other	0.36	0.06	0.17
TFP	0.59	1.02	1.24
ICT Sector	0.27	0.41	0.77
Other	0.32	0.61	0.47
Labour Productivity Growth	1.36	1.54	2.43
Memorandum Items			
ICT Capital Income (%)	3.3	5.3	6.3
ICT Sector Output Share (%)	1.4	1.9	2.5

Source: Oliner and Sichel (2002); labour quality is included in other TFP.

Table 5. Contributions to British Labour Productivity Growth from Steam Power. (% per year)

	1760-1800	**1800-30**	**1830-50**	**1850-70**	**1870-1910**
Capital Deepening					
Steam Engines	0.004	0.02	0.02	0.06	0.09
Railways			0.14	0.12	0.01
TFP					
Steam Engines	0.005	0.00	0.02	0.06	0.05
Railways			0.02	0.14	0.06
Total	0.01	0.02	0.20	0.38	0.21
Memoranda (%GDP)					
Engine Income Share	0.1	0.4	0.5	1.2	2.2
Rail Income Share			0.6	2.1	2.7
Steam Social Saving	0.2	0.0	0.3	1.2	1.8
Rail Output Share			1.0	4.0	6.0

Source: Crafts (2003). The social savings of steam engines are used to estimate the TFP growth contribution.

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