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GROWTH ACCOUNTING IN ECONOMIC HISTORY: FINDINGS, LESSONS AND NEW DIRECTIONS

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Abstract. There is now a large volume of growth accounting estimates covering the long run experience of advanced countries. However, most of the studies in economic history are not based on state-of-the-art methods. There is a trade-off between maintaining international comparability and achieving the best results for individual countries. A one-size-fits-all approach will not always do justice to the variety of historical experiences since the conventional assumptions may sometimes be inappropriate. Nevertheless, growth-accounting studies have produced some eye-catching results which provide food for thought both for economic historians and for growth economists. These include (1) the finding that TFP growth was comparatively slow during the First Industrial Revolution, (2) Solow's famous conclusion that TFP growth accounted for 7/8ths of American labour-productivity growth was atypical, (3) the impact of new general-purpose technologies on growth typically takes a long time to materialize, ICT being the notable exception and (4) that capital-deepening was much more important relative to TFP growth in east Asian than in western European catch-up growth. Growth accounting is undoubtedly a valuable item in the cliometrician's toolkit. Nonetheless, we anticipate the introduction of more sophisticated methods and look forward to progress in understanding what explains marked differences in TFP performance.

Keywords. Economic history; Growth accounting; Long run; Productivity; Technological change; TFP

1. Introduction

Growth accounting came to prominence in the 1950s and early 1960s notably through the work of the National Bureau of Economic Research on long run trends in the American economy which was summarized in Abramovitz (1956) and culminated in the magisterial volume by Kendrick (1961).[1] Solow (1957) put the growth economics into growth accounting, making clear its interpretation in terms of the distinction between shifts of and moves along the aggregate production function. Moves along the frontier represent changes in the available physical capital per unit of labour, whereas residual productivity change not explained by capital deepening causes the frontier itself to shift, captured by Total Factor Productivity (TFP).

As Griliches said, 'This clarified the meaning of what were heretofore relatively arcane index number calculations and brought the subject from the periphery of the field to the center' (1996, p. 1328).[2]

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Although, it was clear that the residual would capture any kind of shift in the production function, the memorable interpretation that Solow's paper invited and that the concluding summary of his paper contained was that 7/8ths of the increase in American labour productivity between 1909 and 1949 was attributable to technological change (1957, p. 320).

Around this time, historical national income accounting was only beginning to produce estimates of long-run growth in various countries. Kuznets was at the centre of these efforts and together with Abramovitz edited a series of commissioned monographs which aimed to develop long run growth accounts for industrialized countries. Several of these volumes eventually came to fruition including Carre *et al.* (1975) on France, Ohkawa and Rosovsky (1972) on Japan, and Matthews *et al.* (1982) for the United Kingdom together with a succession of papers on the United States, culminating in Abramovitz and David (2001). Research was begun at OECD and produced explicitly comparable growth accounts for six countries from 1913 of which the best-known version was eventually published as Maddison (1987).

Since the 1960s, the field of growth accounting has also seen major theoretical contributions, most notably by Dale Jorgenson who stressed the importance of investment in human, physical and intangible capital (Jorgenson and Griliches, 1967; Jorgenson *et al.* 2005). Jorgenson *et al.* (1987) also developed a more general input-output framework, explicitly accounting for the use of intermediate inputs, and integrated growth accounting with index number theory and national accounts. Aided by this solid foundation, growth accounting has become a staple of economic historians' studies of long-run growth. Recently, much of this has been used to compile long-run growth accounts for 23 countries on a standardized basis (Bergeaud *et al.*, 2018).

The potential value of growth accounting in economic history accrues in several ways. First, it is a way of benchmarking and, as such, provides a useful diagnostic of strengths and weaknesses in growth performance. By setting out the proximate sources of growth, a growth-accounting approach delivers key explicanda for deeper analyses of the growth process. Second, extensions of the basic methodology permit the quantification of the contributions to growth made by particular sectors or new technologies. This allows a valuable reality check on over-enthusiastic claims made in the literature and provides a perspective on productivity 'puzzles' such as the Solow Paradox. Third, the agenda of trying to understand the underpinnings of Solow's residual, and thus explicitly to confront 'the measure of our ignorance', offers valuable insights into the nature of productivity advance and the large differences in TFP levels across countries.

Even so, it is important to recognise that growth-accounting estimates may be sensitive to the details of the methodology used. Even within traditional neoclassical growth accounting, best practice has evolved over time. Notably more sophisticated methods of measuring factor inputs tend to be used in modern studies, in particular, taking account of capital and labour services. On the other side of the equation, measuring real output correctly is also particularly important in historical growth accounting, as we will discuss below. At a more fundamental level, the imposition of a Cobb–Douglas production function with disembodied Hicks-neutral technological progress may lead to seriously biased results in some historical circumstances or it could be argued that new growth economics would suggest different growth accounting formulae.

There is also a deeper concern with the use of growth accounting to identify the sources of growth which was very clearly articulated by Abramovitz (1993) in his presidential address to the Economic History Association. The issue is interdependence: both between the opportunities presented by the nature of technological change for capital accumulation and between the trajectory of physical and human capital formation and technological change. While the latter is now stressed by some endogenous-growth models, it is actually the former which is highlighted by a comparison of the American growth process in the 19th and 20th centuries.

If technological change is taken to be endogenous, the main implications are for the interpretation of estimates of the sources of growth rather than their construction. The direction of causality may be thought to run from factor input growth to TFP growth rather than vice versa as in the traditional neoclassical setting.[3] Growth accounting does not offer a way to test these hypotheses so further evidence is required to obtain a deeper understanding of the growth process. Nevertheless, the insights of endogenous innovation models do suggest possible ways to explore the underpinnings of the residual notably through expanding the framework to incorporate intangible capital including R & D.

In this paper, we review the state of play with regard to growth accounting in the economic history literature for now-advanced countries. After a brief review of the building blocks of growth accounting, we begin by considering some of the main results that have been published and the methods that have been used to obtain them. Then we discuss important lessons which can be taken from this body of work. Finally, we point to some opportunities to extend the scope of research in this area.

2. Basic Concepts

Central to growth accounting is the question how to describe the relationship between inputs and outputs in the aggregate production function. In economic history this relationship is often captured using a standard Cobb–Douglas production function:

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

where Y, L and K are, respectively, output, labour and physical capital and α and $1 - \alpha$ are the output elasticities of capital and labour, and A represents Total Factor Productivity (TFP). This specification exhibits diminishing returns to factor accumulation – increasing any factor of production while keeping the other factor(s) constant will diminish the output per unit of the variable factor – as well as constant returns to scale – doubling all the factors of production will also double output. Generally, it is assumed that production factors are paid their marginal products in which case α and $(1 - \alpha)$ are also the shares of profits and wages in income, respectively. Dividing both sides of the equation by labour (L), taking logs and using growth rates gives us the basic growth accounting equation

$$\Delta\ln(Y/L) = \alpha\Delta\ln(K/L) + \Delta\ln A \tag{2}$$

TFP is usually interpreted as a measure of technology, summarizing how intensively and efficiently inputs are used in production. Not only do we typically find that TFP explains a significant part of labour productivity growth over time, but in cross-country studies we also see that the level of TFP tends to be higher in high-income countries (Feenstra *et al.*, 2015).

This broad interpretation of TFP leaves open a lot of questions not often addressed in the economic history literature. How should we measure human and physical capital? Are there more factor inputs (apart from labour and capital) that we should include in the equation? How should we interpret and measure technology, is it factor neutral as assumed in equation (1), or does it augment one production factor in particular (Bernard and Jones, 1996)? As we will discuss below, none of these issues are particularly easy to address and any departure from the basic production function will make it more difficult to compare results between (historical) growth accounting studies.

In equation (1), the most general and still often used measure of labour is the total number of employees or workers employed in production. A welcome refinement is the inclusion of average working hours. Particularly in long-run studies of productivity, taking the effective hours-of-work into account can really impact results (de Jong and Woltjer, 2011). Average working hours nowadays are well below 1900 levels and show considerable differences between countries (Huberman and Minns, 2007).[4]

Another extension to the basic measure of labour is to make a quality adjustment by distinguishing among several different types of labour inputs, weighted by their average wages and earnings. An often-used distinction is between high- and low-skilled labour based on the listed occupation or the years of schooling of the worker.[5] The differences in average earnings between the labour categories can be thought of as reflecting differences in their marginal productivity. When this adjustment for labour quality is used in a growth accounting framework, output growth as a result of better educated and trained workers is ascribed to input growth – referred to as *labour services* – rather than productivity or technology growth (Jorgenson *et al.*, 2008).[6]

A simple measure of capital input often takes the (real) value of the physical stock of capital, either observed directly as the book- or market value of all assets used in production, or indirectly observing investment flows and imputed rates of depreciation. The indirect method, or Perpetual Inventory Method (PIM) – which rests on the idea that stocks constitute the accumulation of flows of investments, corrected for depreciation and write-offs – usually relies on standardized asset lifetimes, meaning specific assets depreciate at the same rate for different countries and at different times. For historic purposes these asset lives may not be representative. Indeed, Gordon (2016) argues that asset lifetimes increased substantially during the Depression era in the United States as a result of the collapse of investment. Capital input can also be based on *capital services*. Instead of measuring the total value, or wealth of all capital equipment and structures in place, this measure captures the capital service flows derived from these capital assets. The difference between the two approaches is that capital services weight the growth of capital assets by their respective rental prices, whereas capital stocks weight assets by their asset price (Jorgenson *et al.*, 2008).

Correcting for the flows of labour and capital services yields a purer measure of the basic inputs and, as a result, provides a cleaner measure of the growth of TFP as well (Denison, 1962; Griliches, 1963; Gordon, 2010; Bakker *et al.*, 2019). It is not obvious that labour and capital are the only relevant inputs, however. Intangible capital – the result of investment in research and development, market development and organizational and management efficiency for instance – can be hard to measure, but are often seen as crucial drivers of economic growth.[7] The addition of new arable land or the discovery of natural resources can also greatly boost output in a country while leaving labour and capital used in production unchanged, erroneously suggesting greatly improved TFP or substantial technological change.

For productivity studies at the industry level, it may be more appropriate to rely on gross-output as the measure of production, thus incorporating intermediate inputs into the growth account. Exchanging labour or capital inputs for more or better-quality intermediate inputs could show up as an improvement in value-added based TFP. A gross-output based approach would correctly identify this merely as a substitution effect. This approach was already used in the early growth accounts for the United States by Griliches and Jorgenson (1967) and has been successfully applied for a wider sample of Asian, European and American countries in the World KLEMS project (O'Mahony and Timmer, 2009; Jorgenson and Sickles, 2018).[8]

At the left-hand side of the growth account equation (2), the proper measurement of real output – be it value added or gross output – is critical as well. As the example below for growth in Britain during the First Industrial Revolution illustrates, any revision to output growth will change growth of the residual by the same amount. Addressing the index-number issues in the original British GDP deflator substantially lowered both output and TFP growth, discrediting Rostow's (1960) notion of 'take off'. Measuring price changes correctly remains challenging even for more recent periods, both for outputs and inputs like capital goods, particularly those new to the market, which lack a market price altogether or whose quality improves rapidly. As noted by Hulten (1991), hedonic pricing techniques can be used to tackle this issue, albeit under restrictive assumptions. For desktop computers, for example, the price per transistor has declined much more rapidly than the price of computers themselves; using the quality adjusted price index thus inflates the quantity index for computers substantially, more accurately reflecting the actual speed of innovation (Sichel, 2019).

The deflation of value added poses its own unique problem. As value added is generally calculated as the residual of gross output and the intermediate inputs used in production, the price index for value added should ideally also combine the price change of both output and intermediate inputs. This is referred to as double deflation. Prices for intermediates can deviate substantially from those of outputs, meaning estimating real value added using a gross-output deflator (single deflation) will bias the results (Oulton *et al.* 2018). Even so, single deflation is still common practice in historical growth accounting studies, primarily because price data for intermediate inputs is often not available and the double deflated price index can become sensitive to changes in the relative prices of outputs and inputs; even turning negative in some cases (Schreyer, 2001).

The final hurdle to the estimation of TFP in the basic Cobb–Douglas specification is identifying the value of the factor share (α). In the economic history literature, we often see either a fixed value for the factor share of capital somewhere in the range of 0.25 and 0.40, or a variable share based on the observed factor prices for capital and labour.[9] This implicitly assumes that the actual social marginal products are either fixed or are always equal to the marginal wage rate and rental price of capital (Barro, 1999a). Through much of the 20th century in advanced countries the share of GDP paid to capital and labour has indeed been relatively stable, but in the twenty-first century the share of capital has been expanding rapidly (Kaldor, 1961; Jones, 2016).[10] Generally, evidence from growth- and development accounting suggests assuming a constant capital share of one-third is a good approximation of alpha in long-run or cross-country benchmarking studies (Aiyar and Dalgaard, 2005).

The aggregate production function in equation (1) also assumes that technological change augments both capital and labour to the same degree (Hicks neutrality), the production possibility frontier is continuous and has diminishing returns to either factor of production. There is no reason to assume that a shift in the production function always exhibits Hicks-neutral technological change, however. It is fairly straightforward to rewrite the production function so that technological change only affects the productivity of labour (Harrod neutral) or is purely capital augmenting (Solow neutral). In general, one is quite flexible in the choice of production function. For example, relying on the more generalized constant elasticity of supply (CES) or translog production function is perfectly plausible, but the results for the growth account will tend to be different from those based on equation (1). Any deviation from the basic, Hicks-neutral Cobb–Douglas production function will thus make it more difficult to compare results between (historical) growth accounting studies. Then again, care should be taken in always imposing the same functional form and set of assumptions for all countries and years. There is a trade-off between comparability and respecting specific historical circumstances that might render standard assumptions inappropriate. The bias introduced by constraining the functional form may vary over time, affecting long-run studies in economic history to a greater degree than contemporary growth accounting exercises.

Regardless of the choice of production function or the exact specification of the factor inputs, the interpretation of TFP is still not clear-cut. Apart from technological progress, it will likely also comprise several other elements. These elements can reflect the misallocation of factor inputs, market-improvements through better competition policy, market integration, specialization, or even omitted variables and measurement error (Hulten, 2001). Rossi and Toniolo (1992) and Crafts and Mills (2005) apply an alternative to traditional growth accounting proposed by Morrison (1993), not relying on conventional assumptions, but instead applying econometric techniques to account for scale economies, fixed factors of production and adjustment costs, arriving at something much closer to pure technological change. For the long-run comparison of British and German TFP growth in manufacturing, Crafts and Mills conclude that traditional estimates of TFP suffered from a sizable bias and, crucially, that this bias was not constant across time or space, depending on the circumstances. For the interwar USA economy, Inklaar *et al.* (2011) confirm that classical growth accounting produces biased estimates of technological change in the presence of market power and the hoarding of labour and capital. Following Basu *et al.* (2006), they calculate a 'purified' measure of technological change and find robust evidence of short-run increasing returns to scale, contrary to the standard assumption of constant returns to scale in the Solow residual.

So far, we presented a conventional or 'primal' definition of TFP, where the rate of TFP growth is defined as the difference between the growth of real output and the weighted average growth of real physical and human capital. Griliches and Jorgenson (1967) demonstrate that TFP can also be computed from indices of prices for output and input, instead of quantities. The reasoning behind this 'dual' approach to productivity change is very similar to that of primal TFP: any price reduction for output not resulting from the (weighted) change in nominal wages or the rental price of capital represents a shift in the production function. Griliches and Jorgenson (1967) show that under the same assumptions – e.g. constant returns-to-scale and perfect competition – the primal and dual approaches will yield identical results. Even if these assumptions were to be violated; however, Antràs and Voth (2003) show that primal and dual estimates of TFP would be biased to the same degree, as both measures are theoretically equivalent. The frequently observed differences between estimates for the primal and dual approach are more likely the result of inconsistencies in how prices and quantities are measured in the national accounts or the use of a different production function or disparate factor shares (Hsieh, 2002; Aiyar and Dalgaard, 2005). Given that growth accounting studies typically require data on both quantities and prices, the dual approach can be valuable as a robustness check for primal growth accounting studies (see e.g. Bakker *et al.*, 2019).

As noted above, growth accounting is not restricted to the total economy level. The same principles can be applied to study productivity growth at the sectoral or even industry level. Performing productivity analysis at the disaggregate level generally provides a better understanding of the sources behind aggregate growth; not only can we estimate technological change at the sectoral level, the effects of shifts in the structure of the economy on aggregate economic growth can also be captured explicitly (Jorgenson *et al.* 2005).

Moreover, disaggregated growth accounts have been used to evaluate the contribution of General-Purpose Technologies (GPT). The growth accounting equation (2) above can be extended to include both the Capital (K) and TFP relevant to a particular GPT, in this case ICT:

$$\Delta\ln(Y/L) = \alpha_{KO}\Delta\ln\left(\frac{K_O}{L}\right) + \alpha_{KICT}\Delta\ln\left(\frac{K_{ICT}}{L}\right) + \mu\Delta\ln A_O + \phi\Delta\ln A_{ICT} \quad (3)$$

where K_{ICT} is capital used in ICT production, K_O is the rest of the capital stock, A_{ICT} is TFP in ICT production, and A_{O} is TFP in the rest of the economy. The weights for TFP, μ and ϕ, are based on the sectoral weights of other production and ICT respectively. Domar (1961) demonstrated that the correct weights were sectoral gross output divided by GDP.

Equation (3) considers only an industry's TFP growth contribution's direct effect. There could, however, exist indirect effects through TFP spillovers. This would amount to a redistribution of the TFP across sectors, rather than raising aggregate TFP growth for the total economy. However, no generally agreed method exists for measuring TFP spillovers. For electricity's impact on American manufacturing in the 1920s, David (1991) uses an OLS regression to estimate the effect of the growth of electrical motors on the TFP growth acceleration at the sectoral level relative to the previous period. This implies that there is an addition to the output elasticity for electrical capital over and above its factor share weight since a significant effect was found.

3. A Flavour of Growth Accounting Results

Table 1 is designed by its authors to facilitate international comparisons. The dataset by Bergeaud *et al.* (2018) covers 23 countries and can be found at www.longtermproductivity.com.[11] Several points can be taken from this table. First, it is clear that crude TFP growth typically accounts for a substantial fraction of labour productivity growth but, that said, the United States in the mid-20th century is an outlier at 82% in 1913–1950. Second, even after taking account of educational attainment, TFP still frequently emerges as a strong component of labour productivity growth. Pre-1950 Japan is an obvious exception to this as to a lesser extent is the United Kingdom. The range of educational contributions is quite narrow – only 0.13 to 0.64 percentage points per year. Third, the Golden Age of growth from the 1950s to the 1970s in Europe and Japan stands out as a period of very rapid productivity growth which was based, in particular, on exceptional TFP growth.

Table 1. Contributions to Labour Productivity Growth in the Long Run (% per Year).

	Y/HW	K/HW	Crude TFP	Education	TFP
USA					
1890–1913	1.62	0.57	1.05	0.14	0.91
1913–1950	3.30	0.61	2.69	0.42	2.27
1950–1974	2.71	0.63	2.08	0.41	1.67
1974–1990	1.31	0.39	0.92	0.36	0.56
France					
1890–1913	1.92	0.49	1.43	0.30	1.13
1913–1950	2.46	0.34	2.12	0.13	1.99
1950–1974	5.54	1.45	4.09	0.46	3.63
1974–1990	3.05	1.18	1.87	0.27	1.60
Germany					
1890–1913	1.89	0.51	1.38	0.23	1.15
1913–1950	1.49	0.38	1.11	0.16	0.95
1950–1974	5.61	1.68	3.93	0.64	3.29
1974–1990	3.21	1.12	2.09	0.22	1.87
UK					
1890–1913	0.79	0.19	0.60	0.23	0.37
1913–1950	1.44	0.36	1.08	0.19	0.89
1950–1974	3.32	1.50	1.82	0.63	1.19
1974–1990	2.09	0.76	1.33	0.51	0.82
Japan					
1890–1913	2.49	1.60	0.89	0.55	0.34
1913–1950	2.45	1.15	1.30	0.49	0.81
1950–1974	7.10	2.49	4.61	0.51	4.10
1974–1990	3.52	1.60	1.92	0.33	1.59

Notes: Authors' adjustment for age of capital as proxy for capital quality is omitted.
Source: based on Bergeaud *et al.* (2018) with updated estimates supplied by the authors.

During the European Golden Age there was a very strong inverse correlation between the rate of economic growth and the initial level of income. This was an era of strong catch-up growth where traditional growth accounting estimates show that formidable rates of TFP growth were recorded in the lower income economies of Southern Europe (cf. Table 2). When TFP growth is as rapid as it was for Europe during the Golden Age it can be expected that there is a substantial component from reductions in inefficiency, both allocative and productive.

Maddison (1987) in a rather speculative exercise concluded that much of the Solow residual was typically attributable to some combination of labour quality, improved allocation of resources including structural changes in employment, changes in the utilization of factors of production (reconstruction in Germany and Japan), reductions in technology gaps and economies of scale, leaving only a modest share 'unexplained' − and perhaps reflecting disembodied technological change.[12]

Some of these points have been further elaborated since. Regression analysis of comparative growth confirms that reconstruction contributed very strongly to productivity growth in West Germany especially during the 1950s as the disruption of the immediate postwar period ended but was a non-trivial part of

Table 2. Sources of Labour Productivity Growth during Catch-Up (% per Year).

	Y/HW	K/HW	Education	TFP
1950–1974				
Italy	6.71	2.35	0.43	3.93
Portugal	5.32	1.81	0.46	3.05
Spain	5.94	1.72	0.33	3.89
1950–1970				
Czechoslovakia	3.35	1.30	0.30	1.75
Hungary	3.55	1.15	0.30	2.10
Poland	2.35	-0.10	0.60	1.85
1960–1990				
Singapore	4.96	3.34	0.31	1.31
South Korea	4.88	2.78	0.85	1.25
Taiwan	6.14	3.08	0.59	2.47

Notes: The impact on labour productivity for an additional year of schooling is 7% except in Czechoslovakia, Hungary and Poland where it is 13.4% for the first 4 years, 10.1% for the next 4 years and 6.8% after the first 8 years. Estimates from Bosworth and Collins adjusted to per hour worked basis.
Sources: Bergeaud *et al.* (2018); Bosworth and Collins (2003); Vonyo and Klein (2019).

the TFP growth story in most Western European Countries (Vonyo, 2008).[13] Van Ark (1996) undertook sectoral growth accounting and calculated the impact of both intrasectoral productivity growth and shifts in sectoral shares on the basis of a 10 sector analysis. He concluded that, while intra-sectoral productivity growth dominated overall, structural change added 1.4, 1.2 and 0.9 percentage points per year, respectively, to Golden Age growth in Italy, Spain and West Germany.[14]

Orthodox 'shift-share analysis assumes that the intra-sectoral productivity growth rates are unaffected by the labour transfer. This will not be the case, however, if there was surplus labour in agriculture (Kindleberger, 1967). Broadberry (1998) proposed a way to address this issue which has found some favour. He suggested that in a declining sector, such as agriculture, a modified shift-share calculation should be used in which the actual labour productivity growth should be replaced by a counterfactual productivity growth rate obtained by actual output growth minus national labour force growth. Not surprisingly, the contribution of structural change is much larger using Broadberry's method. For example, Prados de la Escosura (2017, p. 33) found that it indicates a contribution of 2.4% per year in Spain during 1950–1974 compared with 0.6 using a conventional shift-share analysis. Nevertheless, while some correction for surplus labour probably is justified, there is no definitive way to make it. It should also be noted that this issue will need to be re-visited if growth accounting is implemented on a labour-services basis since the re-deployment of labour entails an upgrade in labour quality.

As Krugman (1994) highlighted, and, as economic historians in the Gerschenkronian tradition might have predicted, rapid catch-up growth in the east−Asian developmental states looks rather different from the earlier European experience.[15] Krugman relied heavily on a well-known growth accounting exercise by Young (1995) and placed heavy emphasis on his TFP growth estimate for Singapore, which grew at only 0.2% per year. Later researchers have been sceptical of this result for reasons noted in section 2. First, it has been suggested that capital's factor share (0.49) overestimates the output elasticity of capital partly because it is distorted by high mark-ups (Kee, 2002; Sarel, 1997). Second dual growth accounting estimates constructed by Hsieh (2002) show TFP growth at 1.6% per year for 1968–1990.

Bosworth and Collins (2003) undertook traditional growth accounting for South Korea, Singapore and Taiwan – imposing $\alpha = 0.35$ – which confirms that the contribution of capital deepening was formidable and exceeded that of TFP growth in the period 1960 to 1990, notwithstanding that TFP growth was still very respectable. Nevertheless, as Table 2 reports, there is a strong contrast with the well-known cases of Italy, Portugal and Spain in the Golden Age where – despite similarly low initial levels of labour productivity – a far smaller share of catch-up growth was driven by capital deepening.[16]

It has been argued that Cobb–Douglas assumptions might be inappropriate in these East Asian countries since elasticity of substitution between capital and labour (σ) appear to have been much lower than unity and technological change was labour-saving rather than neutral (Rodrik, 1997). In that case, as is well-known, TFP growth will be underestimated by the conventional methodology with its assumption of constant factor shares since growth of the capital to labour ratio with $\sigma < 1$ would lead capital's share to decrease in the absence of technological change. Nonetheless, a correction for this problem would still leave East Asian TFP growth substantially below the European catch-up cases. For example, if $\sigma = 0.6$, the calculations in Felipe and McCombie (2001) suggest this would add about 0.8 percentage points per year to TFP growth in each of Singapore, South Korea and Taiwan.[17]

If the revelation from growth accounting for the East Asian countries was that TFP growth was relatively low compared with Western European catch-up growth, the unexpected finding from recent investigation of Eastern European countries was not just the weak growth performance during the Golden Age, but the very weak contribution from capital deepening, especially in the late-communist years (Vonyo and Klein, 2019). Czechoslovakia, Hungary and Poland had income levels on a par with the Southern European countries in 1950 but grew more slowly subsequently. An unconditional convergence growth regression suggests the penalty for being on the wrong side of the iron curtain was about 1.3 percentage points per year slower growth during the Golden Age (Crafts and Toniolo, 2005).

4. The First Industrial Revolution

One of the most interesting findings from research in quantitative economic history is that the acceleration in economic growth during the British industrial revolution was quite modest relative to later experience. The transition to modern economic growth took several decades and Rostow's notion of 'take-off' (1960) which dominated the literature 50 years ago is now seen as inappropriate.

The main reason for this new perspective is that estimates of the growth of industrial output and real GDP have been revised downwards for the years at the heart of the Industrial Revolution in the early 19th century (see Table 3). In that table, 'Feinstein', who took output growth from the work of Deane and Cole (1962), represents the earlier school of thought, 'Crafts' connotes revisions made in the 1980s and early 1990s, while 'new' incorporates the most recent output growth estimates. There were serious index-number problems with the early estimates of real GDP growth, which used a price index not equivalent to a GDP deflator to convert estimates of nominal GDP to real values. Early attempts to measure industrial output growth gave the fast-growing cotton industry far too high a weight. It is now generally agreed that for this period it is best to measure real GDP growth from the output side and a major project reported in Broadberry *et al.* (2015) is the current state of the art. Table 3 also reports improved estimates of factor input growth but these have a relatively minor impact on estimates of TFP growth.[18] A key message is that measuring real output growth well is fundamental for growth accounting.

A major implication of the new estimates of output growth is that TFP growth was far from spectacular, as is reported in Table 3 which shows crude TFP growth, rising from 0.29% to 0.71% per year during the classic industrial revolution period. Nevertheless, it should be noted that TFP growth accounted for nearly all labour productivity growth which averaged 0.2%, 0.3% and 1.1% per year in 1760–1800, 1800–1830 and 1830–1860, respectively.[19]

Table 3. Accounting for Output Growth (% per Year).

	Capital contribution	Labour contribution	Land contribution	TFP growth	Real GDP growth
Feinstein					
1760–1800	$0.35 \times 1.0 = 0.35$	$0.50 \times 0.8 = 0.40$	$0.15 \times 0.2 = 0.03$	0.32	1.1
1800–1830	$0.35 \times 1.4 = 0.49$	$0.50 \times 1.4 = 0.70$	$0.15 \times 0.4 = 0.06$	1.45	2.7
1830–1860	$0.35 \times 2.0 = 0.70$	$0.50 \times 1.4 = 0.70$	$0.15 \times 0.6 = 0.09$	1.01	2.5
Crafts					
1760–1800	$0.35 \times 1.0 = 0.35$	$0.50 \times 0.8 = 0.40$	$0.15 \times 0.2 = 0.03$	0.22	1.0
1800–1830	$0.35 \times 1.7 = 0.60$	$0.50 \times 1.4 = 0.70$	$0.15 \times 0.4 = 0.06$	0.54	1.9
1830–1860	$0.35 \times 2.5 = 0.88$	$0.50 \times 1.4 = 0.70$	$0.15 \times 0.6 = 0.09$	0.83	2.5
New					
1760–1800	$0.35 \times 1.1 = 0.38$	$0.50 \times 0.9 = 0.45$	$0.15 \times 0.5 = 0.08$	0.29	1.2
1800–1830	$0.35 \times 1.6 = 0.56$	$0.50 \times 1.3 = 0.65$	$0.15 \times 0.1 = 0.02$	0.37	1.6
1830–1860	$0.35 \times 2.9 = 1.02$	$0.50 \times 1.1 = 0.55$	$0.15 \times 0.1 = 0.02$	0.71	2.3

Note: All estimates are derived on standard neoclassical assumptions with the weights as follows: capital = 0.35, land = 0.15, labour = 0.5.
Source: Feinstein (1981) adjusted to 3-factor formula using land growth as in Crafts (1985); Crafts (1985) with revisions from Crafts and Harley (1992); new estimates based on data from Thomas and Dimsdale (2017) and land growth from Allen (2009).

Table 4. The Industrial Revolution in Britain and the Second Industrial Revolution in the United States, 1780–1941.

	United Kingdom, 1780–1860				United States, 1899–1941			
	TFP	*Share of*			TFP	*Share of*		
	growth	VA	IGC		growth	VA	IGC	
	(% p.a.)	(%)	(%)	(%-point)	(% p.a.)	(%)	(%)	(%-point)
Modernised sectors	1.2	29	65	0.33	2.1	23	38	0.49
Remainder	0.3	71	35	0.18	1.0	77	62	0.80
Total	0.5	100	100	0.51	1.3	100	100	1.29

Note: The most progressive sector was cotton textiles (1.9% TFP growth p.a., accounting for 26% of aggregate TFP growth) in the United Kingdom and electric utilities (5.0% p.a. and accounting for 5% of aggregate TFP growth) in the United States.
Source: Bakker *et al.* (2019).

Prima facie, this may seem surprising given that we think of the industrial revolution as a time of extraordinary inventions. Clearly, especially given the imperfections of the underlying economic data, a persuasive narrative is required if these estimates are to gain widespread acceptance. To some extent, this can be provided through the arithmetic of growth accounting by pointing to the large weight of sectors such as domestic service that are known to have been untouched by technology and the small initial size of industries which were transformed, such as cotton textiles. A relatively few 'modernized sectors' dominated TFP growth, as is reported in Table 4. Also, to some extent, the limits to TFP growth

Table 5. GPTs: Contributions to Labour Productivity Growth (% per Year).

	Capital-deepening	TFP	Total
Steam (UK)			
1760–1830	0.011	0.003	0.014
1830–1870	0.18	0.12	0.30
1870–1910	0.15	0.16	0.31
Electricity (USA)			
1899–1919	0.04	0.06	0.10
1919–1929 (1)	0.07	0.07	0.14
1919–1929 (2)	0.07	0.30	0.37
1929–1941	0.04	0.16	0.20
ICT (USA)			
1974–1995	0.41	0.36	0.77
1995–2004	0.78	0.72	1.50
2004–2012	0.36	0.28	0.64

Note: Contributions comprise capital deepening from use and TFP from production. TFP spillovers included in TFP contribution in 1919–1929(2) row, see the text. Price fall for ICT equipment includes computer, software and telecoms; the price of computers alone fell much faster (22.2% per year in the first period and 18.3% per year in the second period).
Source: Growth accounting: Bakker *et al.* (2019), Byrne *et al.* (2013) and Crafts (2004).

during the industrial revolution can be understood through the lens of endogenous growth theory (Crafts, 1995). Nevertheless, some of the strongest support comes from further explorations in growth accounting. Independent estimates based on the dual approach using evidence on real rewards to factors of production broadly support the Crafts-Harley view (Antras and Voth, 2003). Not surprising, since the industrial revolution is notorious for the slow growth of real wages, but the growth-accounting equivalences are often overlooked.

The process of technological advance was characterized by many incremental improvements and learning to realize the potential of the original inventions. This took time in an era where scientific and technological capabilities were still very weak by later standards. Steam power offers an excellent example. The estimates in Table 5 show that its impact on productivity growth during the classic industrial revolution years was trivial, as was made clear originally by von Tunzelmann (1978). In 1830, only about 165,000 horsepower were in use, the steam engine capital share was 0.4% and the Domar weight for steam engines was 1.7% (Crafts, 2004). 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.

5. Great Inventions and American TFP Growth

Steam is generally regarded as one of the three top general-purpose technologies (GPTs) alongside electricity and ICT. As noted in the previous section, the arithmetic of growth accounting reveals why the initial impact of these GPTs was relatively modest. Despite rapid growth in the use and productivity of the new technology, at the outset it comprises only a small share of the capital stock and has only a small weight in the economy as a whole. This is the background to the Solow Productivity Paradox proclaimed in 1987, namely, that 'you can see the computer age everywhere except in the productivity statistics.'[20] To an economic historian, the true paradox is that Solow's ICT paradox was regarded as such, given that by earlier standards, as Table 5 shows, the contribution of ICT in the late 1980s was already stunning even though microchip technology only appeared in 1959.

The estimates in Table 5 for the impact of electricity are more tentative partly because it is difficult to measure the growth of the relevant capital stock to allow for quality change. Still, the sharp drop in prices for computers, semiconductors and software, which drove the contribution of ICT, was much less pronounced for electric motors or for steam horsepower during the first and second industrial revolutions (Crafts, 2004; Edquist, 2010; Jorgenson, 2001; Oulton, 2012). The issue of TFP spillovers also complicates matters. Devine (1983) itemized reasons why TFP spillovers might flow from factory redesign in the interwar years. This was facilitated by the shift to electric unit drive machinery, including enhanced configuration flexibility, materials handling, feasibility of single-story plants and lighter factory buildings, all of which were capital-saving. Table 5 shows that, even after including an estimate of these spillovers along the lines suggested by David (1991), the contribution of electricity to aggregate TFP growth is still quite modest. As shown by Bakker *et al.* (2019), it is unlikely that implementing hedonic prices for electrical motors or taking account of delayed depreciation of capital equipment during the Great Depression could boost the contribution of electricity enough to come close to the total contribution of ICT.

Similarly, a comparison of Table 5 with Table 3 shows that the contribution of steam to overall TFP growth in the first industrial revolution was initially tiny and never dominant. Interestingly, ICT has accounted for a much greater share of American TFP growth in the recent past both because its annual average contribution was larger than that of the other GPTs in Table 5, but also because TFP growth in the rest of the economy was relatively weak. Over 1974–2012, ICT-producing sectors contributed about 54% of TFP growth, 0.43% per year out of 0.79% (Byrne *et al.*, 2013).

It seems clear that a narrative of TFP growth over the long run cannot be framed around successive dominant GPTs. It is also misguided to suppose that rapid TFP growth was always driven by 'great inventions'. Gordon (2016) discussed the 'second industrial revolution' of the late 19th and early 20th centuries in these terms, highlighting the role of four technology clusters: electricity; the internal combustion engine, together with derivative inventions such as interstate highways and supermarkets; rearranging molecules; and the entertainment, communication and information sector. Bakker *et al.* (2019) estimate the sectors that embodied these clusters contributed 38% of American TFP growth during 1899–1941 (0.49/1.29 percentage points per year): important but nowhere near the whole story.

American TFP growth peaked in the second and third quarters and described an inverted-U shape over the course of the 20th century, as is reported in Table 6 and as Gordon (2016) has emphasized. This chronology may seem surprising and is not fully understood. The strength of TFP growth between the beginning of the Great Depression and the start of World War II is quite remarkable in the context of a massive financial crisis while the slowdown of productivity growth at the end of the century appears to be quite contrary to the predictions of endogenous growth theory.

Table 6 also shows that Solow (1957) was capturing a special phase of American economic history when crude TFP growth (i.e., subsuming labour quality in TFP) completely dominated capital deepening as a source of labour productivity growth. In fact, labour quality growth made a strong contribution prior to World War II which was not fully captured in the pioneering research by Kendrick (1961). Rising educational attainment was the largest but by no means the only reason for this.

Table 6. The Inverted-U of TFP Growth in the United States during the 20th Century (% per Year).

		Contribution from		
	Y/HW	K/HW	Labour quality	TFP
1899–1909	1.84	0.36	0.55	0.93
1909–1919	1.90	0.50	0.76	0.64
1919–1929	2.37	0.27	0.46	1.63
1929–1941	2.48	0.15	0.46	1.86
1948–1960	3.28	1.04	0.26	1.98
1960–1973	3.29	0.98	0.10	2.21
1973–1989	1.51	0.84	0.19	0.48
1989–2000	2.27	0.96	0.34	0.97

Note: Capital-deepening contribution based on capital stock prior to 1929 and capital services thereafter.
Source: Database underlying Bakker *et al.* (2019) and BLS (2014).

6. Lessons from the Historiography

Building on the examples reviewed above, a number of reasonably robust lessons can be drawn from the practice of growth accounting in economic history. These have implications for future research as well as for the interpretation of past growth performance.

First, it is clear that TFP growth is not a synonym for technological change. While Solow (1957) put the growth economics into growth accounting and showed that the residual could potentially be interpreted as a measure of the rate of technological change, in practice, this is generally not the case. Indeed, the estimated rate of TFP growth can be either an under- or an overestimate of the contribution of technological change to labour productivity growth.

There are two important cases where it will be an underestimate. First, as has been highlighted by the controversy over East Asian growth, if technological change is labour-saving and the elasticity of substitution is less than one, then the rate of TFP growth obtained by imposing standard assumptions of a Cobb–Douglas production function with neutral technological change is too low. Second, if technological change is embodied in new types of capital goods, as economic historians often suggest and is common in endogenous-growth economics, then the technological change contribution would subsume both TFP and part of what is normally counted as capital-deepening (Hulten, 1991; Barro, 1999b). This is, of course, exactly the way that growth accounting for the impact of GPTs has been conducted.

On the other hand, especially when TFP growth is rapid, as in famous cases of catch-up growth, it is likely that there is a substantial component from reductions in inefficiency, increased capacity utilization and economies of scale. The attempt at decomposing the residual in Europe's Golden Age by Maddison (1987) reflects this quite clearly. Recent research has emphasized that inputs are inefficiently used even in very successful developing economies such as China and India (Hsieh and Klenow, 2009) and a similar degree of inefficiency characterized American manufacturing in the late 19th century (Ziebarth, 2013). Reduction of inefficiency is evidently an important avenue for TFP growth during economic development. Conversely, when growth accounting estimates indicate negative TFP growth over lengthy periods, as in much of Africa over the last decades of the 20th century (Bosworth and Collins, 2003), this seems much more plausibly interpreted as reflecting worsening problems of inefficiency and capacity utilization rather than technological regress, which would entail 'forgetting' production methods.

Second, when Solow (1957) was published, the 'capital−fundamentalist' view of economic development predominated. In terms of economic history, this was encapsulated in the idea of

Table 7. Traditional versus Modern Growth Accounting: Spain, 1850–2000.

	Y/HW	K_{stock}/HW	Education	TFP (1)	K_{serv}/HW	LQ	TFP (2)
1850–1883	1.2	0.5	0.1	0.6	0.6	0.0	0.6
1884–1920	1.0	0.6	0.1	0.3	0.6	0.1	0.3
1921–1929	2.0	0.5	0.1	1.4	0.6	0.5	0.9
1930–1952	0.0	0.2	0.3	−0.5	0.2	0.0	−0.2
1951–1974	5.5	1.1	0.4	4.0	1.2	0.6	3.7
1975–1986	6.1	1.9	0.8	3.4	1.9	0.9	3.3
1987–2000	1.1	0.7	0.6	−0.2	0.8	0.1	0.2

Note: TFP (1) is based on educational attainment as a proxy for labour quality and TFP (2) is based on an estimate of labour quality using relative wage rates to weight labour inputs.
Source: Prados de la Escosura and Roses (2009, 2010).

take-off based on a doubling of the investment rate proposed by Rostow (1960) and based on his understanding of the British industrial revolution. Subsequent research has shown that the investment rate rose only slowly and that capital deepening accounted for very little of the labour productivity growth during the industrial revolution (Crafts, 2018). More generally, as we saw in Section 3, it is clear that, even after many refinements to the pioneering crude TFP estimates, TFP growth has generally made a substantial contribution to economic growth in western countries albeit not as large a fraction as the 7/8ths of labour productivity growth proclaimed by Solow originally. Capital fundamentalism is dead notwithstanding the brief period when AK growth models were popular 30 years ago.[21]

The East Asian miracle was at one point interpreted by some as an example of economic development based on capital fundamentalism (Krugman, 1994). This seems inappropriate for a number of reasons. In fact, even though TFP growth as conventionally measured was a bit disappointing it was well above zero (cf. Table 2). The significance of this goes beyond the direct contribution to growth through an indirect impact via the speed with which the incremental capital to output ratio increases and diminishing returns set in. In other words, the rate of growth of the capital stock and the profitability of investment was underpinned by TFP growth as was emphasized by Nelson and Pack (1999).

Third, it is important to recognise that most historical growth accounting studies are not based on modern best practice. Jorgenson (2018) stresses that in the case of the later 20th-century United States, the use of modern growth accounting methods (notably moving to a capital services and labour quality basis) has meant that a much greater proportion of labour productivity growth (about 80%) is now attributed to factor inputs and less to TFP (about 20%) – roughly the opposite of the conventional wisdom of sixty years ago. This suggests an important agenda for economic historians, namely to see if making these methodological innovations for past episodes of growth makes a similar difference. So far, estimates based on capital services and labour quality rather than capital stocks and educational attainment of the labour force are still relatively uncommon. To a large extent, this reflects data limitations.

The most ambitious attempt to develop long-run growth accounting estimates using such an approach is by Prados de la Escosura and Roses (2009) (2010) and its results are summarized in Table 7. Actually, the Spanish case suggests that adopting a capital services measure of capital inputs makes only a small difference at any time during the period 1850–2000. Similarly, estimates for the United States during 1929 to 1941 were made on a capital services basis by Bakker *et al.* (2019) and they showed capital input growth contributing 0.1 percentage points per year more than using capital stocks. A recent paper which provides estimates for Italy from 1861 onwards using a capital services-based methodology (Giordano *et al.*, 2017) finds a somewhat bigger effect but in no period is the difference between this approach and the traditional one greater than 0.26 percentage points per year.

Table 8. Crude TFP Growth in Major Sectors (% per Year).

	UK, 1873–1913	UK, 1924–1937	USA, 1919–1941
Agriculture	0.4	2.1	2.1
Mining	−0.1	1.2	2.7
Manufacturing	0.6	1.9	3.8
Construction	0.1	1.3	0.7
Utilities	1.6	1.8	3.9
Transport & communications	0.7	1.0	3.1
Commerce	0.5	−0.5	1.1
GDP	0.4	0.7	2.2

Note: Crude TFP means that labour quality (education) is not separately accounted for.
Source: Bakker *et al.* (2019); Matthews *et al.* (1982).

Measuring labour inputs using a labour quality approach has a bigger impact in Table 7. Interestingly, whether educational attainment or labour quality implies the bigger contribution varies over time. Moving from traditional to modern growth accounting has a maximal total effect of a 0.5 percentage point reduction in estimated TFP growth in 1921–1929 most of which comes from the contribution of labour inputs. The study of the United States by Bakker *et al.* (2019), summarized in Table 6, also found that using a labour quality approach reduced estimated TFP growth substantially – by 0.4 percentage points per year compared with Kendrick (1961) on average over 1899–1941. On the evidence so far, it appears that making a serious attempt to measure labour quality better may matter more for the improvement of historical growth accounting than trying to estimate capital services.

Fourth, the value of international comparisons for benchmarking growth performance is apparent. Tables 1 and 2 offer an excellent example. The failure of Eastern European countries in both capital deepening and TFP growth during the Golden Age stands out more clearly in a comparative context. Also, spelling out the different types of catch-up growth experienced by East Asia and Western Europe puts the controversy over the East Asian miracle into a much clearer perspective.

Nevertheless, one of the most powerful examples can be found by considering the Matthews *et al.* (1982) volume in the Abramovitz-Kuznets series which examined UK growth without developing an adequate comparative viewpoint. Not surprisingly, perhaps, traditional views of interwar UK economic performance were pessimistic. Revisionist accounts appeared in the 1960 and 1970s and their relatively favourable interpretation was echoed by the emphasis placed by Matthews *et al.* (1982, pp. 506–507) on a U-shaped pattern in TFP growth with a low in the early 20th century followed by a revival in the interwar period leading on to an all-time high after World War II. From a domestic perspective this may seem quite encouraging.

However, growth accounting estimates reported in Table 8 show that productivity growth in the United Kingdom continued to be well below that of the United States. There was an improvement compared with the early 20th century but during 1924 to 1937 labour productivity growth and TFP growth were below the levels of 1873–1899. In sharp contrast, TFP growth in the United States rose to new heights which were sustained through the 1930s. The revival of TFP growth stressed by Matthews *et al.* (1982) is more apparent at a disaggregated level, as can be seen in Table 8, where most sectors, notably including manufacturing, achieved much stronger TFP growth in 1924–1937 than in 1873–1913. The big exception to this was ‘commerce’ (distribution, finance and miscellaneous services) which detracted significantly from overall TFP growth. Poor performance in commerce may have reflected disguised unemployment in hard times. Again, however, in most sectors, including manufacturing, interwar TFP growth in the United Kingdom was well below the American level. Notably, the United Kingdom struggled to match American productivity performance in the industries at the heart of the second industrial revolution. Comparing Britain in 1924–1937 with the United States in 1919–1941, crude TFP growth in vehicles/transport equipment was 3.1% per year compared with 6.5%, in electrical engineering/electric machinery it was 2.0% compared with 5.0%, and in chemicals 1.4% compared with 4.8%. These UK–USA comparisons suggest that the pessimists were right after all.

7. Where Next?

Understanding the reasons for success and failure in productivity performance across countries over the long run is a central task for economic history. Conventional growth accounting is a key building block in this endeavour. In this section we highlight two complementary research techniques which can deliver further insights, namely, levels accounting and frontier analysis.

Levels accounting seeks to quantify the proximate sources of the differences in income levels across countries at a specific point in time.[22] Income differences are attributed to differences in observed levels of labour and capital inputs, with the remainder attributed to differences in TFP. Mirroring the approach taken by growth accounting, one typically assumes a countries' output, *Y*, is produced using a basic Cobb–Douglas production function under constant-returns to scale with a constant elasticity of capital, α (Caselli, 2005). All factor inputs and outputs are divided by the countries' workforce, *L*, and expressed relative to a base country, say the United States. Country *m*'s relative GDP per capita is thus defined as $\tilde{y}_m = \frac{Y_m/L_m}{Y_{US}/L_{US}}$, and the basic production function as:

$$\tilde{y}_m = \tilde{k}_m^{\alpha} \tilde{h}_m^{1-\alpha} A_m \tag{4}$$

where *k* is the capital intensity relative to the United States and *h* is human capital per worker. The left-hand panel of Figure 1 provides a graphical example of levels accounting. Here the gap in output per worker (*y/l*) between countries 1 and 2 is decomposed into the difference in TFP and capital intensity (*k/l*) levels (ignoring educational attainment, *h*). The former is represented by the vertical distance between the production frontiers for both countries at the level of capital per worker for country 1. The effect of the higher capital intensity level for country 2 is represented by the increase in output per worker resulting from a shift along country 2's production frontier.

Hall and Jones (1999) note that, in levels accounting, it is likely that countries are on their steady state level, where capital has already fully responded endogenously to the level of technology. A more appropriate production function would thus rewrite the decomposition based on the capital-to-output ratio (*K/Y*):

$$\tilde{y}_m = \left(\frac{\tilde{K}_m}{\tilde{Y}_m}\right)^{\frac{\alpha}{1-\alpha}} \tilde{h}_m A_m \tag{5}$$

Until very recently, levels accounting for the period before 1950, where the coverage of the Penn World Tables begins, has been uncharted territory (Feenstra *et al.* 2015). A major limitation has been the availability of suitable data on human and physical capital inputs. It is possible that more analysis can now be carried out and this is a significant opportunity since levels accounting is a valuable tool for evaluating comparative economic performance as it reflects the cumulative impact of accumulation and TFP growth over the preceding period.

Recent research by Gallardo Albarrán (2018) has made an important start in this regard through using historical national accounts data to estimate physical capital stocks for 38 countries in the early decades of the 20th century. His results contrast with those typically found for modern data which find that TFP is much more important than factor inputs in explaining the variance of income levels and the higher productivity of rich compared with poor countries. The opposite seems to have been true in the early

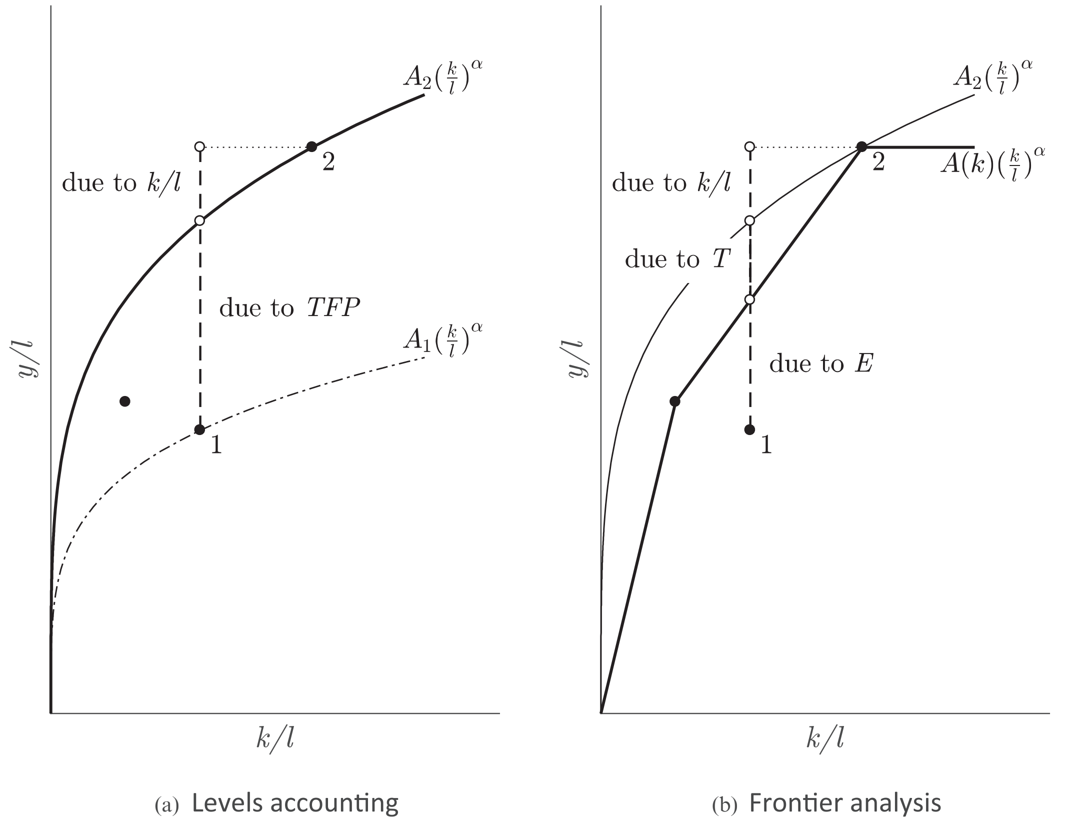

Figure 1. Levels Accounting and Frontier Analysis.

Table 9. Accounting for Income Variance across Countries (%).

	1900	1929	1950	1973	1990	2008
Due to factor inputs	59	59	37	39	28	30
Due to TFP	41	41	63	61	72	70

Note: estimates based on the Hall and Jones (1999) method but a similar story results from using the Caselli (2005) formula.
Source: Gallardo Albarrán (2018).

decades of the 20th century while the dominance of TFP was established between 1929 and 1990 (see Table 9).

Prima facie, the implication of these findings seems to be that the 20th-century acceleration of technological progress in advanced countries which was concentrated in technologies that were inappropriate for much of the rest of the world led to a new configuration which was not observed in an earlier phase of modern economic growth which saw relatively modest TFP growth not only in Britain, as noted above, but also in the United States during the 19th century (Abramovitz and David, 2001).[23] This hypothesis deserves further exploration and a richer account may emerge in due course which examines in detail obstacles to the international diffusion of technology and the complementary role of differential reductions in inefficiency.

Issues relating to the international diffusion of technology can be explored by applying another technique, frontier analysis (Woltjer, 2018). This technique explicitly allows for a bias in technological change, meaning technological change can be faster at higher levels of capital per unit of labour.[24] Indeed, Allen (2012) shows that technological change was strongly biased towards higher levels of capital intensity between 1820 and 1990. Most technological progress was achieved by rich-world countries, shifting the production frontier only locally. Consequently, countries with an input mix deviating from the R&D leader were unable to benefit from the most productive technologies (Jerzmanowski, 2007). Remarkably, developing countries appeared to be no more productive in 1990 than countries with a similar capital-intensity level in 1820 (Allen, 2012). In contrast, traditional growth and levels accounting generally assumes technological change grows uniformly at all levels of capital intensity. As noted by Timmer and Los (2005), the assumption that advances in, say, (capital-intensive) high-speed maglev trains would improve the performance of (labour intensive) rickshaws by a similar multiple is clearly wrong, undermining the applicability of growth models based on a classical Cobb–Douglas production function.

The right-hand panel of Figure 1 provides a graphical example of frontier analysis. Instead of estimating the production function using equation (4), the production frontier is formed as linear combinations of observed 'best-practice' activities (Salter, 1966). An observation is best-practice if increasing any output or decreasing any input is possible only by decreasing some other output or increasing some other input (Koopmans, 1951). In this example, both country 2 and the unlabelled country to the left of country 1 are classified as best-practice. Country 1 is located below the frontier; its vertical distance to the frontier (E) indicates the potential for labour-productivity increase through using the production factors at hand more efficiently.

This analysis is especially useful in considering success and failure in catch-up growth, as the discussion of Europe's Golden Age by Abramovitz and David (1996) underlines. They emphasize that catch-up growth is not automatic but depends on 'social capability' and 'technological congruence'. In terms of Figure 1, the former relates to the elimination of the productivity gap due to E and the latter to the productivity gap due to T. Their approach is one of conditional convergence and their argument is that lack of social capability and technological congruence had held Europe back prior to World War II but these constraints on growth were much reduced by the 1950s and 1960s. Technological congruence refers to the cost appropriateness of the leader's technology in the follower countries which can be undermined by differences in factor intensities. Social capability refers to the ability to assimilate new technology. Absorptive capacity is underpinned by education, skills and economic competences including organizational effectiveness, appropriate business models and training. Beyond this, however, social capability turns on institutions, economic policies and the incentive structures that they imply, which affect the profitability of innovation and investment.

The methodology of frontier analysis offers a way to bring quantification to these concepts which have proved somewhat elusive for cliometricians. Jerzmanowski (2007) made a pioneering attempt to implement this approach and a summary of some of his results in shown in Table 10. These show that TFP gaps were still quite large in 1960 but that they were primarily due to shortfalls in efficiency rather than technology gaps. Subsequently, big reductions in these efficiency gaps by 1985 accounted for a good part of European catch-up. This tends to confirm that American technology was congruent for early postwar Western Europe.

The diagnosis of 'inefficiency' made by an analysis of this kind is potentially a bit misleading even though there are good reasons to think that countries which are engaged in rapid catch-up growth often have an opportunity to improve resource allocation quite markedly (Hsieh and Klenow, 2009). The decomposition of the TFP gap is a diagnostic rather than an explanation. For example, part of the shortfall

Table 10. Decomposition of 1960 Level of TFP into Efficiency and Technology Components (USA = 1.00).

	TFP	Efficiency	Technology
Austria	0.60	0.64	0.94
Belgium	0.65	0.64	1.01
Denmark	0.69	0.68	1.01
Finland	0.62	0.60	1.04
France	0.72	0.71	1.01
Greece	0.49	0.57	0.86
Ireland	0.51	0.55	0.93
Italy	0.67	0.71	0.94
Netherlands	0.77	0.74	1.04
Norway	0.54	0.63	0.86
Portugal	0.57	0.66	0.87
Spain	0.64	0.74	0.86
Sweden	0.73	0.72	1.01
Switzerland	1.05	1.00	1.05

Note: TFP = Efficiency × Technology.
Source: Jerzmanowski (2007).

Table 11. Decomposition of Labour Productivity Growth based on Frontier Analysis, UK 1907–1930.

	Annual average growth rate (ln%)			
	Total	Capital accumulation	Technological change	Efficiency
Total manufacturing	**1.9**	**1.7**	**1.4**	**−1.2**
'Old staples'	*1.7*	*1.2*	*1.3*	*−0.8*
Textile and apparel	2.5	1.2	1.6	−0.4
Building materials	2.1	1.0	1.5	−0.4
Metals	0.7	1.1	1.3	−1.7
'New industries'	*1.8*	*2.5*	*1.7*	*−2.4*
Paper and printing	2.5	3.3	1.2	−2.1
Chemicals and rubber	1.3	1.9	2.3	−2.9
Machinery	0.5	0.5	0.4	−0.5
Transportation equipment	3.6	3.6	3.0	−3.0

Source: Woltjer (2013).

due to E may relate to the absorptive capacity aspect of social capability. This is illustrated by Woltjer (2013) in his consideration of the Anglo-American productivity gaps before World War II.

Growth of labour productivity in UK manufacturing between 1907 and 1930 (1.9% per annum) was respectable but fell well behind the growth in US manufacturing (3.1% per annum). As illustrated in the first row of the decomposition in Table 11 – an example of frontier analysis where the United States effectively serves as the frontier – the cause of this disappointing growth was a sharp decline in efficiency. At the same time, rapid capital accumulation, over double the American rate, helped keep British labour productivity growth well above zero. At the disaggregate level, the fall in efficiency is most evident for 'new industries', those that stood most to gain from the innovations of the Second Industrial Revolution, such as chemicals and transportation equipment. Here capital accumulation was more rapid, particularly compared to the ‘old staples’ like textiles and metals.

Woltjer argues that this strong correlation is no accident. He shows that technological change in the new industries was generally faster and, crucially, heavily biased towards capital intensive forms of production. This provided a strong incentive for British producers to adopt American mechanised production techniques that exhibited substantial growth potential, resulting in rapid capital deepening in these new industries. This increased growth potential was not realized immediately however, as is evident from the rapid decline in efficiency. Following Basu and Weil’s (1998) appropriate-technology model, the decrease of relative efficiency in Britain can be interpreted as a feature of modernization inextricably linked to the first phase of catch-up growth, that is creating potential. Only after an economy has adjusted to the new situation and has achieved the full potential of the new technology can the labour-productivity gap to the frontier be closed. Efficiency decline can thus be interpreted as the result of learning-by-doing and not as the consequence of wasteful production techniques or mismanagement. This analysis offers additional insight into the comparisons of Anglo-American TFP growth reported in Table 8.[25]

8. Conclusions

There is now a large volume of growth accounting estimates covering the long run experience of now advanced countries. This includes a database constructed to facilitate international comparisons. The standard approach is to impose a Cobb–Douglas production function and neoclassical assumptions about factor shares. Most of these estimates are not based on state-of-the-art methods in that they do not use a capital services or labour quality approach to the measurement of inputs for which the underlying data may not be readily available. There is inevitably a trade-off between maintaining international comparability and achieving the best results for an individual country. This is accentuated by the possibility that the one-size-fits-all approach does not do justice to the variety of historical experience since on occasions the conventional assumptions may be quite wide of the mark.

Nevertheless, research in this tradition has produced some eye-catching results which probably are reasonably robust and provide food for thought both for economic historians and for growth economists. These include the finding that TFP growth, and it would seem the economic impact of technological progress, was quite modest and slow to accelerate during the First Industrial Revolution notwithstanding the famous inventions of the period. It is also now clear that Solow’s famous result that crude TFP growth accounted for 7/8ths of American labour productivity growth over the 40-year period that he studied is not typical of other times and places. Indeed, the evidence is that American TFP growth followed an inverted-U shape during the long 20th century which is quite contrary to the predictions of endogenous (although not semi-endogenous) growth models. It has also become clear that the impact of new general-purpose technologies on labour productivity growth typically takes quite a long time to materialize as is exemplified by the cases of electricity and steam. This highlights that the impact of ICT was remarkably strong after a relatively short time contrary to the presumptions of the Solow productivity paradox. Finally, the finding that capital-deepening was much more important relative to TFP growth in east Asian than in western European catch-up growth offers important insights into the ‘developmental state’ although without validating Krugman’s gloomy assessment.

The basic ideas of growth accounting can also be used to examine reasons for differences in income levels across countries. Levels accounting has been used to investigate this issue for many countries in the modern era and the Penn World Tables make this relatively straightforward. The general result of such exercises is that TFP is a good deal more important than factor inputs in accounting for the gaps between rich and poor countries. New estimates suggest that this was much less true a century ago and that the dominance of TFP is a fairly recent phenomenon. This finding deserves further investigation but, if it is indeed robust, it opens up an important avenue of research in the context of identifying more clearly changing obstacles to the international diffusion of technology as well as looking at the evolution of efficiency levels in countries at different stages of development.

Solow described TFP as the 'measure of our ignorance'. To a large extent this is still a valid comment. We certainly should not regard the rate of TFP growth as a synonym for the rate of technological progress. Frontier analysis is potentially an important technique in this context and can be used as a diagnostic to decompose differences in TFP into components relating to efficiency and to technology. This may help to provide some quantification for the notion of social capability introduced by Abramovitz as a key concept with regard to catch-up growth especially if ways are found to explain the efficiency gaps.

Growth accounting is still a valuable item in the cliometrician's toolkit. Conventional methods have delivered and will no doubt continue to provide important results. At the same time, we look forward to the introduction of more sophisticated methods and supplementary analyses which can build on the excellent progress already made.

Notes

1. The basic idea of a decomposition of the sources of growth into contributions from factor inputs and from output per unit of total input had already been made explicit by Tinbergen (1942) and Stigler (1947).
2. Solow (1957) was aware of the NBER work and his estimates were based on it. He clearly saw himself as clarifying the economic interpretation of their results and underlining the strong assumptions needed to interpret the residual as technological change (p. 317).
3. These issues are explored in detail by Aghion and Howitt (2007).
4. As noted by Ward et al. (2018), correctly measuring average hours of work for the total economy is not straightforward. Often labour force surveys (LFS) are used to estimate hours-of-work. Since coverage of these LFS is rarely complete, adjustments made to include the informal sector, unpaid labour by household members or a correction for the bias in self-reported hours are crucial. These measurement issues are as relevant today as they are for (cross-country) historical growth accounting studies.
5. More refined measures can also include, among others, work-experience and gender as distinguishing factors.
6. The work of Denison (1962, 1985) was one of the first serious attempts to capture education's impact on labour quality, using estimates of educational attainment and associated wage differentials, very similar to the approach favoured by Jorgenson. Denison did, however, make an arbitrary assumption to discount 40% of these differentials as due to intrinsic ability and disregarded changes in working hours (see Gordon, 2000).
7. Investment in intangible capital was limited prior to the Second World War, making this less of an issue in historical growth accounting (Corrado et al., 2009).
8. The acronym denotes the inputs recognized in this approach; capital (K), labour (L), energy (E), materials (M) and services (S).
9. Alternatively, the factor shares can also be imputed by regressing the growth of output on the growth of capital and labour. The intercept would capture TFP growth while the coefficients give the factor share of capital and labour (Barro, 1991).
10. Recent empirical research suggests that imperfect competition in the American economy implies that the share of wages underestimates the output elasticity of labour, especially after 2000. This means that the output elasticity of capital is overestimated by the share of profits and that the conventional estimate of TFP growth in the American business sector is biased downwards by an average of 0.24 percentage points per year over the period 1948 to 2015. A similar bias is already apparent prior to 1973 (Dixon and Lim, 2018)

11. To provide comparability and cover a lengthy period meant that it was not possible to produce estimates on a capital-services and labour-quality basis.
12. It should be noted that the results of a data envelopment analysis give strong support to the claim that TFP growth during the European Golden Age was boosted considerably by improvements over time in the efficiency of factor use (Jerzmanowski, 2007).
13. There was, however, no bonus from reconstruction effects in Eastern Europe (Vonyo, 2017).
14. This paper, as is typical in economic history, takes only a subset of possible sectoral shift effects into account, compared with the state of the art among economists. Notably Diewert (2015) provides a decomposition technique that measures the contribution of the growth of sectoral labour productivity, real output prices and sectoral labour input shares to aggregate labour productivity.
15. In a very influential contribution, Gerschenkron (1962) proposed that the growth of ‘backward’ follower countries would differ from that their predecessors. In particular, there would be a much greater emphasis on capital accumulation and a key role for what would later be called the ‘developmental state’ in implementing this.
16. However, it should be noted that in the early stages of modern economic growth in Western Europe in the 19th-century TFP growth did not dominate capital-deepening which was the more important source of labour productivity growth in cases such as Austria, Spain and Sweden (Crafts, 2009).
17. It should also be noted that a similar correction might be appropriate for the European catch-up cases in which, according to recent estimates (Mallick, 2012), σ was well below 1 and lower than in the East Asian countries.
18. All the series underlying the new estimates can be found in a spreadsheet compiled by Thomas and Dimsdale (2017). The growth accounting in Table 3 follows a standardized format to permit comparisons across vintages of estimates and so the estimates differ slightly from those reported in Crafts (2019).
19. Table 3 does not take account of human capital per worker which in any case is unimportant during this period (Crafts, 2019).
20. Robert Solow made this throw away (but much quoted) remark at the end of a book review (Solow, 1987).
21. Capital fundamentalism sees investment in physical capital as the key determinant of economic growth. This is clearly not true in an accounting sense since TFP growth typically makes a sizeable contribution. Growth accounting does not establish causation but it seems implausible that TFP growth can be seen as simply a result of investment in physical capital.
22. Note that levels accounting is often referred to as ‘development accounting’ in the economics literature.
23. Using traditional growth accounting, Abramovitz and David (2001) find that TFP growth in the United States was 0.2% per year between 1800 and 1855 and 0.4% between 1855 and 1890. This may be somewhat underestimated if, as these authors thought, the elasticity of substitution was less than 1 in this period.
24. Surprisingly few studies in economic history have incorporated frontier analysis; for another example see Timmer *et al.* (2016).
25. The post-1930 period was rather different as UK productivity performance was undermined by protectionism and a retreat from competition (Crafts, 2012).

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