The Mystery of TFP

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ABSTRACT

The objective of this article is to critically examine explanations of Total Factor Productivity (TFP) growth. TFP growth is analysed at the sectoral and aggregate level, using data for 10 industry groups covering the market sectors of 18 countries over the period 1970-2007 drawn from the EU KLEMS dataset. In all countries resources have been shifting away from industries with high TFP growth towards industries with low TFP growth. Nevertheless structural change has favoured TFP growth in most countries. Errors in measuring capital or in measuring the elasticity of output with respect to capital are unlikely to substantially reduce the role of TFP in explaining growth. The article concludes that the mystery of TFP is likely to remain as long as measurement error persists.

It is generally agreed that increases in labour productivity are the only long run source of growth in living standards. And since Solow (1956) a wide though not universal consensus has existed that behind the growth of labour productivity stands the growth of Total Factor Productivity (TFP). Without continuing TFP growth there can be no growth in labour productivity since capital accumulation by itself would be subject to diminishing returns. But what are the sources of TFP growth? The literature (surveyed by Hulten (2001)) suggests that *measured* TFP growth can arise in one or more of the following ways:

- From technical and scientific progress (including improvements in management techniques). This does not include progress embodied in new or improved types of capital or which is purchased directly via for example consultancy. Only progress which comes for free is to be included here.
- From learning effects, either learning by doing or learning from others, or more broadly from externalities and economies of scale.
- By reallocation of inputs towards more (or less) productive uses, either at the firm or the industry level.
- As an artefact of measurement error (as when increases in the quality of human or physical capital are wrongly ignored or output is mismeasured) or when some types of asset (such as intangibles) are wrongly omitted.

A particular concern in the literature has been the role of capital. In the past, at least some of measured TFP growth would have been rightly attributed to the fact that indices of capital input were crude, e.g. horsepower. And some, includ-

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ing the originator of TFP as a theoretical concept and pioneer of its empirical measurement (Solow 1957), thought that price indices of capital goods did not allow for quality change. But nowadays it is accepted that they should and this principle is enshrined in the OECD Productivity and Capital Manuals (OECD 2001 and 2009). But the extent to which capital is well-measured in practice is still open to debate and will be discussed in what follows. The earlier growth accounting literature also paid considerable attention to capital measurement (Griliches and Jorgenson 1967; Jorgenson *et al.* 1987); in particular, it introduced the important distinction between capital stocks and capital services. The result of these pioneering efforts was to reduce but not eliminate the role of TFP.

This article discusses some of the (non-exclusive) explanations of TFP growth listed above. A particular focus is the extent to which they are consistent with the pattern of TFP growth at the industry level. For example, it is not obvious how technical and scientific progress leads, year by year, to TFP growth in retailing. The factors which are important here are likely quite different from those which are important in (say) semiconductors. The fact that industry TFP growth rates differ suggests adding a fifth source of TFP growth at the aggregate level:

- Shifts in the structure of output and demand leading to changes in the aggregate growth rate of TFP and hence of aggregate labour productivity. These shifts could be favourable or unfavourable to growth.

The article therefore employs data from the EU KLEMS dataset to study the properties of TFP growth at the industry level. It seeks to quantify and assess the sources listed above as causes of TFP growth (except I shall have very little to say about the third source). I refer to the "mystery" of TFP since, though almost everyone agrees it is fundamental to growth, there is no consensus as to how much of measured TFP growth should be allocated to each of the five sources just listed. And as we shall see, the likelihood of significant measurement error bedevils further progress in understanding.

The first section of the article describes the EU KLEMS dataset to be used in the empirical work. This dataset provides the broad facts about TFP growth and the allocation of resources to different industries in 18 countries over the 1970-2007 period (though not every country has data for all years).

Section 2 then turns to the issue of structural change (the fifth source of TFP growth) and whether it has tended to increase or reduce TFP growth at the aggregate level. This section is motivated by the observation that resources have been shifting into business services yet this industry has experienced negative TFP growth in 17 out of the 18 countries. The possibility of measurement error (the fourth source) plays an important part here.

Section 3 examines measurement error in more detail, considering whether mismeasurement of capital, usually leading to understatement of capital growth, can account for an appreciable part of measured TFP growth. Such mismeasurement could take the form of understated quality change, missing assets (such as certain intangibles), or failure to account for increases in the variety of capital goods available on the market.

Section 4 analyses whether, even if capital is measured correctly, its impact on growth may not be. There might be externalities which make the elasticity of output with respect to capital greater than the value suggested by capital's share in the value of output (the standard measure in the growth accounting literature); this is the second source of TFP growth. Whether the evidence is more consistent with a two-sector than a one-sector model is also considered. Section 5 concludes.

The EU KLEMS Dataset

The empirical analysis to follow uses data from the EU KLEMS dataset described in O'Mahony and Timmer (2009), which is freely available at www.euklems.net.[2] More specifically, the March 2011 update of the November 2009 release is used. This file contains data on national accounts and growth accounting variables for 29 countries over 1970-2007. In particular, it contains data on TFP (the value added concept), real and nominal value added, real and nominal gross output, labour services and capital services. Estimates of labour input incorporate changes in labour quality. Estimates of capital services distinguish between ICT and non-ICT assets and are estimated on a comparable basis across countries. However, these data are not available for all countries and all years. Data on TFP are only available for 15 European countries (Austria, Belgium, Czech Republic, Denmark, Spain, Finland, France, Germany, Hungary, Ireland, Italy, Netherlands, Slovenia, Sweden, and the UK) and three non-European countries (Australia, Japan and the United States). The maximum number of annual time series observations for a country is 37 (Italy and the UK) and the minimum number is 11 (Slovenia).[3]

The EU KLEMS dataset has two great strengths. First, it is consistent with the national accounts of the countries included. Second, it goes beyond the national accounts by using a common methodology for estimating labour quality and capital services. Furthermore, labour quality and capital services are estimated in a disaggregated manner: 18 types of labour (distinguished by educational attainment (three types), sex (two types) and age (three groups)) and seven types of capital asset (three in ICT and four in non-ICT assets).[4] Labour input is measured by hours worked, not number of workers.

The EU KLEMS dataset therefore contrasts with micro (firm-level or establishment-level) data which are not usually consistent with the national accounts. Also in micro data, estimates of capital and labour are often crude. For example, for capital frequently only nominal book value (a stock not a flow measure) is available which then has to be deflated by an overall deflator. This is generally the case for all studies based on company accounts (e.g. Bartelsman *et al.*, 2013; Hsieh and Klenow, 2009). Studies based on census data usually have to make do with investment, often aggregated over asset types, to which it is difficult to apply the Perpetual Inventory Model. Firm-level prices are usually not available so firm output has to be deflated by an industry deflator; on the rare occasions when firm-level prices can be observed there are often substantial differences between them and the corresponding industry-level deflators (Foster *et al.* 2008). Labour input must frequently be measured by the number of employees.

These criticisms are not meant to disparage micro-level studies, just to point out that the data on which they are based do not dominate empirically the data behind industry-level studies. So micro-level studies should be seen as complements to, not substitutes for, industry-level ones.[5]

2 The EU KLEMS database has been analysed by Timmer *et al.* (2010).

3 Table 1 in the on-line Appendix (csls.ca/ipm/31/oulton-appendix.pdf) provides the time period covered in the 18 countries.

4 ICT assets: computers, communication equipment, and software. Non-ICT assets: transport equipment, other machinery and equipment, non-residential structures, other. Residential structures are also in the EU KLEMS dataset but are not used in productivity analysis.

5 See Syverson (2011) for a survey of work on productivity based on micro data. The focus of much of this work is on explaining why productivity levels differ across firms rather than on explaining differences in growth rates. He does not address the issue of data reliability.

The growth accounting variables in EU KLEMS are broken down by industry in accordance with Revision 1 of the NACE.[6] The analysis to follow is confined to the market sector and its constituent 10 industries for two reasons. First, the measurement of real output in the non-market industry groups is problematic and likely inconsistent across countries. Second, since most of the non-market industries are publicly-owned, the motivations of decision makers are probably not focused on cost minimization or profit maximization, thus calling into question the growth accounting methodology. On average, across all available years and countries for which TFP data are available in EU KLEMS, the market sector as defined here accounted for 71 per cent of total value added and 75 per cent of total hours worked (Table 2 in the on-line Appendix).

In summary, the results to be reported are for 18 countries and the 10 industry groups comprising the market sector over a maximum time span of 1970-2007. The EU KLEMS dataset is in the process of being extended to cover the period of the Great Recession and its aftermath. But at the time this research began, it stopped in 2007. This means that the article can have nothing to say directly about the effects of the financial crisis on TFP, which has led to at the very least a temporary slowdown in growth.[7]

TFP Growth and the Allocation of Resources across Sectors: an Overview

TFP Growth

Chart 1 shows TFP growth in the market sector in the 18 countries, both the actual growth rate and the growth of TFP after smoothing by the Hodrick-Prescott (HP) filter. Most countries show little sign of either accelerating or decelerating growth.[8] Four countries were clearly above their own long run average at the end of our period: Austria, Finland, Netherlands and the UK. And five were by then below their own long run average: Australia, Spain, Ireland, Italy, and Japan, though in the case of Japan and Italy the HP trend is more encouraging. For five others, the data period was too short to allow a conclusion (Czech Republic, Germany, Hungary, Slovenia and Sweden). Much more striking is the difference between countries in their mean growth rate (Chart 2). Bottom of the class is Spain at 0.23 per cent per year and top is Hungary at 2.55 per cent per year (though over a short period). Other strong performers were Austria, Finland, Ireland and Japan.

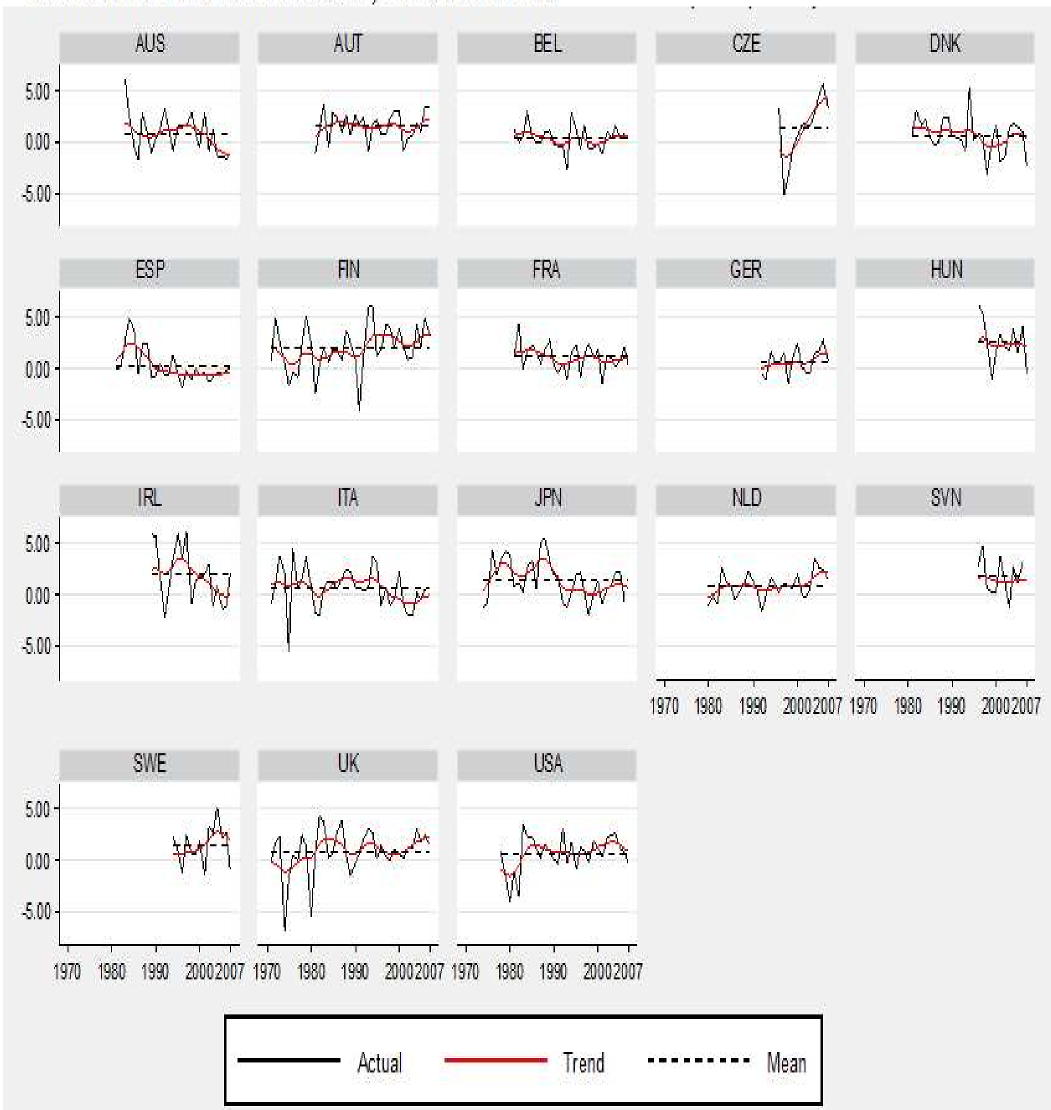
Chart 1 in the on-line Appendix to this articleshows mean TFP growth rates in 10 sectors within the market sector for the 18 countries in the EU KLEMS dataset. The highest growth rates are found in agriculture where the unweighted cross-country mean is 2.86 per cent per year and in manufacturing where it is 2.15 per cent. The lowest are in construction, hotels and restaurants, and business services where the cross-country means are -0.18 per cent, -1.16 per cent and -1.17 per cent respectively. It is

6 For a list of the sectors in the statistical classifications economic activities in the European community (NACE) see Table 2 in the on-line Appendix.

7 See Oulton and Sebastiá-Barriel (2016) who discuss whether the crisis will affect not just the level but also the future growth path of labour productivity and TFP.

8 This contrasts with labour productivity at the whole economy level where there are signs of a pervasive slowdown commencing prior to the global financial crisis, at least in large economies (Cette *et al*., 2016; OECD 2016, chapter 5). For the United States Byrne *et al*. (2016) document slowing TFP and labour productivity growth since 2004.

Chart 1
Growth of TFP in the Market Sector, Per Cent Per Year

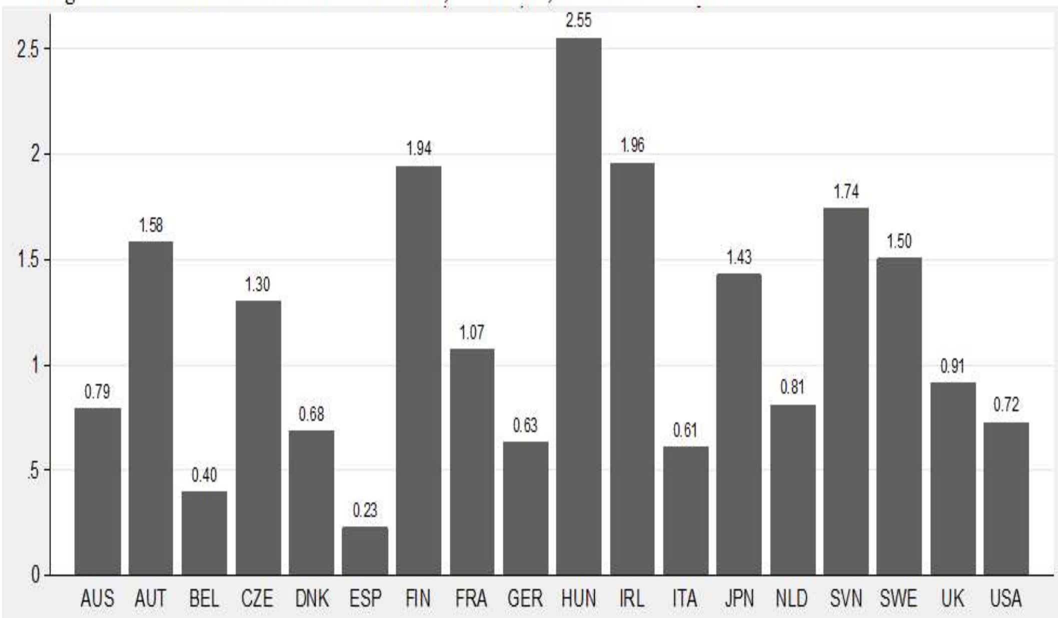


Source: EU KLEMS.
Note: Trend growth rate is that of HP-smoothed TFP level. Dashed lines denote country means of actual TFP growth rate.

worrying that there are a considerable number of negative rates. For example, eight out of 18 countries show negative TFP growth in mining and quarrying, five in electricity, gas and water, nine in construction, twelve in hotels and restaurants, five in finance and no less than seventeen in business services.

Negative TFP growth suggests firms in these industries are becoming less efficient over time or that technical knowledge is being forgotten, which seems highly implausible in peaceful conditions. Negative growth may be explicable in some cases. For instance in mining and quarrying deposits may be becoming harder to extract as they are progressively worked out. In electricity, gas and water an increasing burden of environmental regulation might be the cause: the costs of meeting the regulations are measured but the benefits in terms of lower emissions are not included in output. These explanations do

Chart 2
Average TFP Growth Rates in the Market Sector, 1970-2014, Per Cent Per Year



Source: EU KLEMS.

not seem to apply to construction or hotels and restaurants and still less to business services which as we shall see is one of the sectors to which resources are shifting in all countries.

Hence one must suspect measurement error, as already noted by Timmer *et al.* (2010) in the case of business services. If measurement error is present the first place to look is errors in output measurement. It is well known that price indices for private services are poorly developed by contrast to those for industrial products (though even those are not beyond reproach as discussed below).[9] It is quite plausible that the relative prices of sophisticated services like legal and advertising services or software are falling but that this is not picked up by the deflators actually used (often the GDP deflator or the CPI).

Value Added Shares

The pattern of resource allocation, as measured by the nominal value added share of each sector in market sector GDP, has been changing in all countries (as shown by Chart 2 in the online Appendix). In most countries, the share of agriculture and manufacturing has been declining while that of finance and business services has been rising. The agriculture share is falling in all countries except perhaps the United States. The share of manufacturing has been falling in 11 countries (including even Germany). In construction in most countries the share is flat. The share of wholesale and retail trade shows little change. The share of hotels and restaurants is flat in most countries. Finance displays a rising trend in nine countries though in some the rise is in the first half of our period, e.g. France. The clearest pattern is seen in business services whose share has been rising in every country. This means that in most countries resources have been shifting away from agriculture and manufacturing, where TFP growth is apparently at its most rapid, towards in particular business services where TFP growth is measured as negative. The implications of this (on the face of it) puzzling fact will be pursued in the next section.

9 See Bean (2016, chapter 2) for UK evidence on this.

Structural Change and Increasing Specialization

The first aim of this section is to show theoretically that aggregate TFP growth rises when resources (value added) are shifting towards industries supplying intermediate goods and services. This is the case even when these supplying industries themselves have low TFP growth (provided it is positive). The second aim is to quantify the size of these effects in our 18 countries.

Aggregate and Industry-Level TFP Growth: Theory

Let us begin with a brief review of TFP growth at the aggregate and industry levels; see Oulton (2016) for a more detailed exposition. The growth rate of aggregate TFP (a.k.a. the Solow residual) is defined as

$$\mu := \hat{V} - \alpha\hat{K} - (1-\alpha)\hat{L} \qquad (1)$$

where V is real GDP, K is aggregate capital services, L is aggregate labour input, α is the capital share, and hats denote growth rates. The symbol ":=" denotes a definition. Assuming marginal cost pricing and that a given input receives the same price in all industries, the Solow residual in a multi-industry setting is interpretable as a measure of the outward shift of the production possibility frontier made possible by technological change, with all inputs (including intermediate ones) held constant (Hulten, 1978; Gabaix, 2011, Appendix B).

The economy is made up of different industries and it seems plausible that the rate of technical progress varies across industries. How is the aggregate rate of technical progress related to the rates in different industries? Consider an industry production function

$$Y_i = f_i(K_{i,1}, \ldots, K_{i,C}; L_{i,1}, \ldots, L_{i,D}; M_{i,1}, \ldots, M_{i,N}; t) \qquad (2)$$

Here Y_i is real (gross) output in the i-th industry (i = 1,...,N) and there are assumed to be C types of capital K_{ik}, D types of labour L_{il}, and N types of intermediate input M_{ij} (produced by the N industries but possibly also imported). Now let μ_i^{GO} denote TFP growth in industry i.[10] Taking the logarithmic derivative of the production function with respect to time yields an expression for μ_i^{GO}:

$$\mu_i^{GO} = \hat{Y}_i - \sum_{k=1}^{C} \alpha_{ik}\hat{K}_{ik} - \sum_{l=1}^{D} \beta_{il}\hat{L}_{il} - \sum_{j=1}^{N} m_{ij}\hat{M}_{ij} \qquad (3)$$

where $\alpha_{ik}, \beta_{il}, m_{ij}$ are the elasticities of output with respect to capital, labour and intermediate inputs. Assuming competitive conditions these elasticities can be equated empirically to the share of each input in the value of gross output (the input cost shares).

Given this measure of μ_i^{GO} for each industry, it can be shown that aggregate TFP growth is[11]

$$\mu = \sum_{i=1}^{N} d_i \mu_i^{GO} \qquad (4)$$

10 The superscript "GO" indicates that this is the gross output concept of TFP growth. There is an alternative approach to industry-level TFP measurement based on industry-level value added. The gross output concept of industry TFP growth is more fundamental than the value added one. The value added concept is derived from the gross output one under an additional, restrictive assumption: real gross output per unit of real intermediate input is determined entirely by input prices and can never be reduced by technical progress. It can be shown that the TFP measures based on gross output and value added satisfy the following relationship:

$\mu_i^{VA} = \left[\frac{GO_i}{VA_i}\right]\mu_i^{GO}$, where GO_i and VA_i are the nominal gross output and nominal value added of industry i.

We will use this equation to convert the industry-level value-added-based TFP measures from EU KLEMS into gross output measures, but otherwise we will not use the value added concept of TFP in this article.

11 For this aggregation result to hold we just need to assume that a given input earns the same return wherever it is employed. If this is not the case then the aggregate formulas become more complex with additional terms reflecting the shift of resources to or from industries where they are more highly valued (Jorgenson *et al.* (1987: 66). In this article, these complications are ignored. They are not likely to be of great empirical importance in advanced economies (at least, Jorgenson *et al.* (1987) did not find them important for the United States over 1948-79).

Here d_i is the Domar (1961) weight for the i-th industry, defined as

$$d_i := \left[\frac{GO_i}{GDP}\right] \qquad (5)$$

where GO_i is the nominal gross output of industry *i* and GDP is nominal aggregate GDP.[12]

Increasing Specialization as an Additional Source of Growth

The aggregation result reveals that aggregate TFP growth depends not only on the industry-level TFP growth rates but also on the pattern of demand embodied in the set of Domar weights. This means that structural change - that is, change in the pattern of demand across industries - can lead to changes in aggregate TFP growth even with no change in any industry-level rate of TFP growth. A well known example of this phenomenon is the cost disease model of Baumol (1967). Suppose that over time consumer demand is shifting towards final demand services, such as entertainment, health and education, which have low productivity growth. Everything else being equal, this shift of resources toward industries with relatively low TFP growth reduces aggregate TFP growth.

But this is not the whole story. To see why, consider the Domar weight in more detail. It can be decomposed as

$$d_i = \frac{GO_i}{GDP}$$

$$= \frac{\text{Final Sales by } i}{GDP} + \frac{\text{Intermediate Purchases by } i}{GDP}$$

Consider for simplicity a closed economy. Then there are three points to note. First, the first ratio on the right hand side must be a fraction between 0 and 1 and these fractions must sum to 1 across industries since the sum of final sales equals GDP. Second, the second ratio on the right hand side can take any non-negative value. So the sum over industries of the Domar weights must be at least 1 (and is typically much greater, over 2, as we shall see). Third, it is possible for the sum of the Domar weights to rise over time if the degree of outsourcing (i.e. intermediate sales relative to gross output) is rising generally.

This adds a new source of aggregate TFP growth that is different from those usually considered. Even if industry-level TFP growth were the same across industries and constant over time, an increase in the degree of outsourcing in the economy (reflected in an increase in the sum of the Domar weights) would result in an increase in aggregate TFP growth.

This point is clarified by the following simple example. Consider a closed economy with only two industries. The first industry ("cars") makes only final sales. It buys intermediate inputs from the second industry ("business services") which uses only primary inputs and makes only intermediate sales. Then the Domar weights in the two industries are:

$$d_1 = \frac{GO_1}{GDP} = \frac{VA_1 + M_{1,2}}{GDP} = \frac{VA_1 + VA_2}{GDP} = 1$$

$$d_2 = \frac{GO_2}{GDP} = \frac{M_{1,2}}{GDP} = \frac{VA_2}{GDP}$$

Here $M_{1,2}$ denotes intermediate input sales from industry 2 to industry 1. Since industry 2 uses no intermediates itself and sells all its output to industry 1, $M_{1,2}$ is equal to both the gross output and the value added of industry 2. Since industry 1 produces all the final goods in this economy, its gross output is equal to aggregate GDP.

12 Note that under this approach there is no role for differences in the level of TFP across industries to affect the aggregate TFP growth rate, e.g. by shifts in labour and capital towards industries with a higher TFP level. This contrasts with the situation for labour productivity, on which see for example Reinsdorf (2015). The reason is that a given input is assumed to receive the same return in every industry, so there is no possibility for example of capital earning a higher return in some industries than in others. There is in any case competitive pressure to equalise TFP levels across different industries in a given country (Baumol and Wolff, 1984).

Now, suppose the degree of outsourcing increases, so that industry 1 uses more intermediates to produce a given amount of gross output. Industry 2 produces more intermediates to supply to industry 1. The result is a decrease in the value added share of industry 1 and an increase in that of industry 2 (i.e. $\frac{VA_2}{GDP}$ rises). The Domar weight of industry 1 remains unchanged, but that for industry 2 increases. As long as the industry-level TFP growth rate in industry 2 is positive, this change will result in an increase in aggregate TFP growth via equation (4).[13] This is true even if TFP growth in industry 2 is lower than TFP growth in industry 1.

So we have reached the paradoxical conclusion that the aggregate TFP growth rate can rise even if resources are shifting towards industries with lower productivity growth, provided these industries are selling intermediate and not final products (and provided that TFP growth in these industries is positive; if it is negative, then outsourcing will reduce aggregate TFP growth).[14] Intuitively, productivity growth in industries that produce intermediate inputs contributes indirectly to the output of the final goods industries that buy those intermediates, and it is the output of final goods that is relevant for aggregate productivity growth. Outsourcing (i.e. an increase in the value added share of intermediate input producers) increases the size of this contribution, even with the industry-level productivity growth rates held constant. Oulton (2001) provides a more fulsome discussion of the intuition behind this result.

How Much have the Domar Weights Changed in Practice?

Chart 3 in the on-line Appendix shows the Domar weights over time in the 18 countries in the EU KLEMS dataset for three important sectors: manufacturing, finance and business services. The weight for manufacturing is clearly declining in eight countries, flat in five, and clearly rising in only two. In finance, the Domar weight is rising in 14 of 18 countries. In business services, the weight is rising in all 18 countries.

A clearer picture emerges by collapsing the 10 sectors into three broad groups: the goods-producing or "production" part of the economy; consumer services; and services to other industries, or producer services.[15] The broad picture is that the Domar weight for the goods producing part of the economy has declined in 13 of the 18 countries (the largest declines were in Japan and the UK). For consumer services the weight rose by a modest amount. The weight for producer services services broadly defined (sections I, J and K) rose in all 18 countries and on average by more than the fall in the weight for production. In consequence there was a rise in the sum of the Domar weights in 13 out of the 18 countries. A rise in this sum reflects an increase in outsourcing and would push aggregate TFP

13 In this simplified case the sum of the Domar weights increases; the upper limit of the sum is 2. In general, if there were N-k industries selling final goods and k selling intermediate goods the limit of the Domar sum is again 2. In practice the Domar sum exceeds 2 (even in a closed economy) since all industries have some intermediate sales.

14 This is a qualification to the cost-disease argument in Baumol (1967). The latter is still correct as long as it is understood to refer to industries producing final, not intermediate, products. All this is explained more fully in Oulton (2001). The basic point was generously acknowledged by Baumol in Krueger (2001: 223), in Baumol (2002), pages 277-278, and further analysed in Baumol (2012), particularly chapters 9 and 10 (Wu 2012a and 2012b). Ngai and Pissarides (2007) subsequently showed that Baumol's original conclusion that the aggregate growth rate would decline need not follow in the long run: in a model with capital the equilibrium growth rate is constant even though employment shifts progressively to the stagnant sectors. However their model predicts that value added shares are constant in the long run and this is hard to square with the evidence presented above that these shares have been steadily changing over periods measured in decades.

15 Table 1 in the on-line Appendix provides a full list of the 10 sectors.

Table 1
Change in Domar Weights between First Year and Last Year

Countries	Net Goods Production	Consumer Services	Producer Services	Total
	A-F	G, H	I, J, K	
Australia	-0.255	0.151	0.227	0.123
Austria	-0.086	0.035	0.275	0.224
Belgium	-0.104	0.117	0.371	0.384
Czech Republic	0.179	0.005	0.124	0.308
Denmark	-0.308	-0.024	0.369	0.037
Finland	-0.022	0.050	0.272	0.300
France	-0.290	0.062	0.297	0.069
Germany	0.130	-0.008	0.177	0.299
Hungary	0.152	0.011	0.086	0.249
Ireland	-0.246	-0.027	0.306	0.033
Italy	0.003	0.182	0.369	0.554
Japan	-0.507	0.042	0.222	-0.243
Netherlands	-0.356	0.065	0.268	-0.023
Slovenia	-0.043	-0.017	0.090	0.030
Spain	-0.525	0.050	0.192	-0.283
Sweden	0.054	0.011	0.079	0.144
United Kingdom	-0.697	0.118	0.452	-0.127
United States	-0.458	0.003	0.300	-0.155
Mean	-0.188	0.046	0.249	0.107
Number negative	13	4	0	5

Note: The goods sector includes agriculture, hunting and forestry, and fishing; mining and quarrying; manufacturing; and electricity, gas, and water. Consumer services includes wholesale and retail trade and repair services. Business services includes transport, storage and communications, financial intermediation and business services excluding real estate (see Table 1 in the on-line Appendix).

growth upward if the industry-level TFP growth rates remained constant and positive.

Measuring the Impact of Structural Change

We are now in a position to estimate the impact of structural change on aggregate TFP growth, making use of equation (4):

$\mu = \Sigma_{i=1}^{N} d_i \mu_i^{GO}$

Gross output estimates of TFP growth by industry are not available, but they can be calculated from the value added estimates in EU KLEMS (see footnote 10). Then treating these as parameters we can estimate the effect of different patterns of demand, both final and intermediate (the Domar weights), on the aggregate TFP growth rate. Two natural questions are first, what would the aggregate TFP growth rate have been if the pattern of demand in each country had remained that of the beginning of the period? And second, what would it have been if the pattern at the end of the period had prevailed throughout the period?

Table 2 shows the answers to these two questions. For reference, column 1 shows the mean TFP growth rate in the market sector that was actually observed (as already shown in Chart 2). A first shot at the answers appears in columns (2), (3) and (6). Column (2), headed "Initial structure", shows for each country the mean TFP growth rate with the pattern of demand (the d_i) set equal to the average of the first two years of the sample in each country. Column 3, headed "Latest structure", shows a similar calcu-

Table 2
Effect of Structural Change on TFP Growth in the Market Sector, Per Cent Per Year

		No TFP adjustments		Only business services adjusted		Change in TFP growth due to structural change		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Country	Actual demand structure	Initial demand structure	Latest demand structure	Initial demand structure	Latest demand structure	No TFP adjust-ments	Only business services (B.S.) adjusted	B.S. adjusted to half Market Sector rate
Australia	0.79	0.75	0.60	0.68	0.67	-0.15	-0.01	-0.03
Austria	1.58	1.80	1.69	1.66	1.79	-0.11	0.13	0.06
Belgium	0.40	0.55	0.39	0.50	0.45	-0.16	-0.05	-0.08
Czech Republic	1.30	1.06	1.42	1.04	1.44	0.36	0.40	0.39
Denmark	0.68	0.76	0.95	0.68	0.99	0.19	0.31	0.28
Finland	1.94	2.02	1.90	1.88	2.06	-0.12	0.18	0.10
France	1.07	1.17	1.02	1.08	1.16	-0.15	0.08	0.03
Germany	0.63	0.71	0.69	0.60	0.75	-0.02	0.15	0.14
Hungary	2.55	2.50	2.58	2.50	2.66	0.08	0.16	0.13
Ireland	1.96	1.70	1.72	1.79	1.92	0.02	0.13	0.10
Italy	0.61	0.76	0.44	0.71	0.54	-0.32	-0.17	-0.21
Japan	1.43	1.50	1.36	1.44	1.46	-0.14	0.02	-0.04
Netherlands	0.81	0.83	0.72	0.75	0.83	-0.11	0.08	0.05
Slovenia	1.74	1.85	1.65	1.82	1.65	-0.20	-0.17	-0.19
Spain	0.23	0.33	-0.14	0.28	0.04	-0.47	-0.24	-0.25
Sweden	1.50	1.45	1.54	1.38	1.63	0.09	0.25	0.19
United Kingdom	0.91	1.17	0.66	1.11	0.78	-0.51	-0.33	-0.42
United States	0.72	1.07	0.49	0.94	0.57	-0.58	-0.37	-0.42
Unweighted mean	1.16	1.22	1.09	1.16	1.19	-0.13	0.03	-0.05

Source: EU KLEMS, March 2011 update of the November 2009 release (www.euklems.net).
Note: Column headed "Actual structure": annual TFP growth calculated using the actual, annually-changing weights. Columns headed "Initial structure": annual TFP growth calculated using the average of the Domar weights of the first two available years. Columns headed "Latest structure": annual TFP growth calculated using the average of the Domar weights of the last two available years. "Only business services adjusted" (columns 4, 5 and 7): for each year and country, TFP growth rate of business services set equal to TFP growth rate in the market sector in that year and country; other sector growth rates adjusted to maintain the original market sector growth rate. Column 6: for each year and country, TFP growth rate of business services set to half TFP growth rate in the market sector in that year and country; other sector growth rates adjusted to maintain the original market sector growth rate. "Change in TFP growth due to structural change": TFP growth with latest structure minus growth with initial structure. For each country, TFP growth averaged over the period for which TFP growth is available.

lation but with the pattern of demand set equal to an average of the last two years of the sample. In both columns (2) and (3) the actual TFP growth rates estimated for each industry are used. Column (6) shows the difference between columns (2) and (3): the growth rate under the latest structure minus the growth rate under the initial one.

The effect of structural change is seen to be predominantly negative. Only 5 out of the 18 countries show a positive effect: the Czech Republic, Denmark, Hungary, Ireland and Sweden. The unweighted cross-country mean of the change is -0.13 per cent per year. Arithmetically, the reason for this is clear: in all countries resources have been shifting to business services but in this sector TFP growth is almost invariably estimated to be negative. So any shift of resources towards this sector will seemingly have reduced the aggregate growth rate (it will make an increasingly negative contribution to the Domar-weighted sum).

As noted above the negative TFP growth rate in business services is very implausible. So in the next variant of the calculations, the TFP growth rate in this sector is set equal to the actual market sector TFP growth rate observed in each country and each year. That is, it is assumed that the overall TFP growth rate is correct, but the measured rate in business services is wrong. So there must be offsetting errors in the other sectors which need to be correspondingly adjusted to leave the aggregate rate unchanged.[16] See Oulton (2016) for details of this adjustment.

Columns (4), (5) and (7) show the results after the TFP growth rate in business services is set equal to the market sector rate, with corresponding adjustments to the other sectors. Now a different picture emerges, with 11 countries showing a positive effect of structural change; the unweighted mean of this change is 0.03 per cent per year. Though the overall average effect is small, the effect is quite large for individual countries such as Austria, Denmark, Finland, Germany and Sweden which all received a boost to productivity growth from structural change on the order of 0.1 to 0.3 per cent per year. For the 11 gainers there was an average boost to growth of 0.17 per cent per year. This can be compared to the average TFP growth rate in these countries of 1.4 per cent per year. So the effect is of an economically significant size.[17]

How sensitive is the finding that most countries have gained from structural change to the assumption that TFP growth in business services, correctly measured, equals that of the market sector as a whole? We can test this by setting TFP growth in business services equal to half that of the market sector in each year and each country (column 8 of Table 2). Naturally this reduces the effect of structural change; the cross-country mean increase in TFP growth due to structural change is now -0.05 rather than 0.03. But the pattern of gainers and losers is very similar: ten countries are net gainers and eight are net losers with the winners gaining on average 0.15 per cent per year and the losers losing 0.21 per cent per year.

It is also possible to show the contribution of each sector to the change in overall TFP growth stemming from structural change, based on the assumption that the TFP growth rate in business services is equal to that of the market sector (Table 3 in the on-line Appendix). The contribution of business services to the overall change is positive in all countries, ranging from 0.01 per

16 An alternative, more radical assumption is to adjust the business services rate upwards but to leave the rates in other sectors unchanged, thus raising the overall average. But this would be a dubious move for two reasons. First, insofar as business services are sold to other domestic sectors (rather than exported) an understatement of TFP growth in this sector (say because output is understated) means that TFP growth in the purchasing sectors is overstated. Second, that the aggregate rate is correct or at any rate more accurate than the sectoral rates can be justified by the way in which national statistical ofices (NSIs) estimate real GDP. Typically this is from the expenditure side since expenditure-side price indices like the CPI are considered more accurate than PPIs or service industry price indices; sectoral growth rates are then adjusted so that when aggregated they conform to the estimated growth rate of GDP based on expenditure. Hence the more radical alternative should be rejected.

17 There is a case for adjusting the TFP growth rate in finance as well, because of the well-known difficulties of measuring output here. In finance the TFP growth rate is usually positive but less than the aggregate rate (Chart A2). But adjusting the TFP growth rate of finance as well as that of business services does not make much difference compared with just adjusting business services. Ten countries now show a positive effect and the unweighted mean of the change is plus 0.04 per cent per year (Oulton, 2016).

cent per year to 0.16 per cent per year; it averaged 0.08 per cent per year. But in some countries, notably Japan, the United Kingdom and the United States, this was more than offset by a negative contribution from manufacturing, so that the overall effect of structural change is negative. In other words in these countries deindustrialisation has apparently gone so far as to impact negatively on overall TFP growth.[18]

Mismeasurement of Capital

In this section and the next I ask whether capital is mismeasured and if so, whether the mismeasurement is large enough to substantially reduce or even eliminate the role of TFP in the growth process.

Mismeasurement of Quality Change

It is entirely plausible that capital growth is understated due to understated quality change, i.e. overstated investment goods price indices (Gordon, 1990). But how much does this affect TFP measurement? The traditional argument (Jorgenson, 1966) is that any errors in measuring capital show up on the output side as well as the input side. If the growth rate of capital services is underestimated due to measurement error, this will tend to overestimate TFP growth. But there is an offsetting factor: the growth of GDP will be understated as well. This is because the growth of GDP is a weighted average of the growth rates of the expenditure components, one of which is investment. So the overall error depends on the size of the weights given to investment on the output side (the investment share in GDP) and to capital on the input side (the profit share).[19]

However, these results are for a closed economy. Consider by contrast an economy, typically a small one, which imports all its capital goods. Then there is no error in real GDP since investment is balanced by capital goods imports of equal size. So any error in real investment is canceled out by an equal error in real imports. But capital input is still understated. So in this case there is no offset and the error in capital measurement translates directly into TFP. In this case the TFP error is the profit share times the capital input error. For example, if there is a 1 per cent per year understatement of the growth of capital and the capital share is 0.35 then TFP growth will be overstated by 0.35 per cent per year. The significance of this can be judged by noting that the cross-country mean TFP growth rate was 1.16 per cent per year (Table 2). In general, the TFP error is likely to be larger in small countries than in bigger ones. But errors in measuring capital growth do not seem likely to eliminate TFP as a source of growth. According to Table 3, capital per hour is growing at 3-4 per cent per year. So a 1 per cent understatement of capital growth would be a large error but would reduce TFP growth by only about 0.35 per cent and that is before allowing for any countervailing error on the output side.

All this is for the aggregate economy. But the errors in TFP measurement are likely to be larger at the industry level. The reason is that most industries are users but not producers of capital goods. So there are no offsetting errors on the output side to at least partially cancel out the input side error and so reduce the TFP error. This means that TFP growth in capital-

18 The UK saw the second largest positive effect from business services but the largest negative effect from manufacturing. However, a substantial fraction of the UK's business services output is exported. So for the UK there is a case for revising up the growth rate of market sector TFP if indeed the growth of business services output is understated by conventional price indices. If so, the UK might finish up as a net gainer from structural change.

19 See Oulton (2016) for a methological exposition.

Table 3
TFP, Labour Productivity (LP), Labour Quality (LQ) and Capital Per Hour (KH) in the Market Sector, Per Cent Per Year (average annual rate of change)

Country	TFP	LQ	LP	KH	LP_ Solow	Capital share	Hypothetical Capital Elasticity (γ)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Australia	0.79	0.25	2.12	2.98	1.43	0.354	0.626
Austria	1.58	0.30	2.70	2.55	2.69	0.332	0.938
Belgium	0.40	0.43	2.27	4.77	1.03	0.328	0.386
Czech Republic	1.30	0.45	3.92	5.57	2.61	0.408	0.623
Denmark	0.68	0.33	2.30	4.58	1.30	0.295	0.432
Finland	1.94	0.63	3.86	4.50	3.49	0.289	0.719
France	1.07	0.57	2.59	3.41	2.01	0.264	0.591
Germany	0.63	0.06	1.89	4.73	0.94	0.271	0.386
Hungary	2.55	0.71	3.93	1.82	4.85	0.391	1.770
Ireland	1.96	0.03	3.88	3.61	3.48	0.447	1.066
Italy	0.61	0.12	2.07	3.98	0.92	0.260	0.489
Japan	1.43	0.56	3.48	4.25	2.70	0.343	0.688
Netherlands	0.81	0.37	1.78	2.24	1.58	0.315	0.631
Slovenia	1.74	0.74	5.24	3.46	2.90	0.204	1.304
Spain	0.23	0.55	1.98	3.39	0.91	0.360	0.423
Sweden	1.50	0.40	3.48	4.94	2.62	0.323	0.624
United Kingdom	0.91	0.43	2.47	4.78	1.74	0.285	0.427
United States	0.72	0.33	2.07	3.67	1.40	0.315	0.475
Cross-country mean	1.16	0.40	2.89	3.85	2.14	0.321	0.700

Source: EU KLEMS, March 2011 update of the November 2009 release (www.euklems.net).
Note: LP: real value added per hour worked. LQ: labour quality (labour services per hour worked, LAB_QPH in EU KLEMS). LP_Solow: TFP growth divided by labour share (estimated as LAB/VA in terms of EU KLEMS variables) plus the growth of labour quality. For each country, growth rates are Törnqvist indices built up from sectoral growth rates and are averaged over the period for which TFP growth is available. Capital share (col. 6): 1 minus labour share. The parameter γ (col. 7) is the hypothetical elasticity of output with respect to capital which would reduce TFP growth to zero: see equation (16).

goods-producing industries is likely to be understated and in other industries overstated.

Missing Capital Input

It is possible that whole classes of capital assets have been omitted from the growth accounting calculations because they have been misclassified as intermediate inputs. This argument was first raised in regard to software and R&D. In this case the argument was accepted and expenditures on software and R&D are now recognized as forms of investment in the System of National Accounts (SNA); software but not R&D appears as an investment in EU KLEMS. It has also been argued that there is a whole range of other expenditures, dubbed intangible investment, which should also be reclassified as investment. These include expenditures on building organizational capital, in-house training, and design and marketing.[20] These expen-

20 See Corrado *et al.* (2005) and (2009) for the United States, Dal Borgo *et al.* (2013) for the UK, and Corrado *et al.* (2013) for a comparison covering the United States, Japan and Europe.

ditures have not yet been accepted as investment in the SNA. But changing the SNA is a lengthy process and it is quite possible that some or all of these expenditures will be in a future SNA revision.

The effect of the shift from intermediate goods to investment goods for intangibles on TFP is quite complicated. The level of GDP rises since there are new forms of investment to include. But whether the growth rate of GDP changes depends on whether the new forms of investment are growing faster or slower than GDP. A similar point applies to the growth rate of capital on the input side. In fact the analysis is very similar to the case just considered of mismeasured quality change, except that in addition the various weights involved in the calculation also change. The net effect is that TFP is still an important factor in the growth process. TFP estimates that include intangible capital (Corrado *et al.*, 2013: Table 2) find that TFP accounted for 26 per cent of labour productivity growth in the EU (unweighted average), for 22 per cent in Japan and for 39 per cent in the United States over 1995-2007 (their Table 2). These figures are similar to estimates from the EU KLEMS database. While a fuller accounting for the inputs behind the growth process is clearly desirable, on the evidence so far it does not seem likely to eliminate TFP as a factor or even to change its importance in a growth accounting sense.

Increasing Capital Variety and the Romer Model

In Romer's (1986) and (1990) model of economic growth there is a goods sector with a production function of the following form:

$$Y = L_Y^{1-\alpha}\int_0^A \chi_j^{\alpha} d_j$$

Here a composite good (Y) is produced with the aid of labour (L_Y) and (a continuum of) A types of capital good ($\chi_1, \chi_2, \ldots, \chi_A$). The composite good can be either consumed or invested. In equilibrium the production function can be re-written as:

$$Y = K^{\alpha}(AL_Y)^{1-\alpha}$$

where K is aggregate capital services. This is identical to a standard Cobb-Douglas aggregate production function. Clearly, capital is subject to diminishing returns so the only long run source of growth is the factor A, the number of types of capital good, which acts here like labour-augmenting technical progress. If we apply conventional growth accounting to the goods sector under the usual assumptions we find that TFP growth is given by

$$\mu := \hat{Y} - \alpha\hat{K} - (1-\alpha)L_Y = (1-\alpha)\hat{A}$$

where $(1-\alpha)$ can be measured by the labour share (Barro, 1999). So TFP growth should now be interpreted as the growth in capital variety weighted by the labour share.

Suppose we apply the Romer production function to the EU KLEMS sectors studied here. How then should we interpret conventionally-measured TFP growth? After all, the latter may reflect conventional notions of TFP such as increasing efficiency or manna from heaven technical progress as well as increasing variety. We could in fact trivially expand the Romer production function to incorporate "conventional" TFP as well as increasing variety:

$$Y = BK^{\alpha}(AL_Y)^{1-\alpha}, B > 0$$

where B is conventional TFP, assumed to grow exogenously. Now the ordinary measure of TFP becomes

$$\mu = \hat{B} + (1-\alpha)\hat{A}$$

But how then do we decide how much of measured TFP growth should be attributed to increasing variety and how much to the other sources?

One response is that we should revise the measure of capital to take explicit account of the increasing (or for that matter decreasing) variety of capital types, whether human or physical. After all, the proximate source of productivity growth in the Romer model is more capital though not more of the same capital. And it is now generally accepted by NSIs that investment and capital should allow for increasing quality. So why not also for increasing variety? This is the approach suggested by Feenstra and Markusen (1992). But to apply their method it is necessary to know the range of inputs in every period and the expenditures on each. It is also necessary to know (or estimate) the elasticity of substitution between varieties. At the moment this makes the approach impractical on a large scale. But in principle it could be used to allocate measured TFP growth between increased variety and other sources.

Capital Externalities and the Relationship between TFP and Capital Accumulation

Externalities, Economies of Scale, and Learning-by-Doing: an Upper Limit

The previous section considered whether capital services are generally mismeasured and if so what is the likely size of the resulting error in TFP growth. Another possibility is that even if capital is correctly measured its impact may not be. In other words, the elasticity of output with respect to capital may exceed capital's share. This could be because of economies of scale. But at the industry level such economies seem likely to be important in only a few industries where a square-cube law prevails, such as pipelines or electricity generation. A more plausible reason is network externality effects as a new technology such as the Internet is deployed. Another is learning by doing arising from capital investment, either within the firm or by follower firms learning from early adopters.

If the elasticity of output with respect to capital (the capital elasticity) has been understated by the capital share, then how large would it have to be to eliminate TFP entirely as a source of growth? Suppose our model is

$$y_t = Ak^{\gamma}h_0e^{\lambda t} \qquad (6)$$

where y is output per hour, k is capital per hour, h is human capital per hour worked (labour quality), λ is the growth rate of labour quality, and γ is the capital elasticity, which is now not necessarily equal to the capital share. Assume that TFP (A) is constant over time (though not necessarily across countries). Then the growth of output between time 0 and time t is given by

$$ln(y_t/y_0) = \gamma ln(k_t/k_0) + \lambda t$$

from which we can solve for γ:

$$\gamma = \frac{ln(y_t/y_0) - \lambda t}{ln(k_t/k_0)} \qquad (7)$$

The parameter γ is therefore the hypothetical capital elasticity which would reduce TFP growth to zero. Columns (2)-(4) of Table 3 show the data necessary for calculating this parameter. Column (7) shows the resulting estimates while Column (6) shows the actual capital share for comparison. On average the hypothetical elasticity is more than twice as large as the actual share. This seems far too large a difference to attribute to network effects or learning-by-doing. Apparent exceptions are Belgium and Spain where the hypothetical elasticity is only about 12 per cent larger than their actual capital shares. But this is because both countries had exceptionally low TFP growth (Column (2)).[21]

We can also test the hypothesis that the capital elasticity exceeds capital's share econometri-

21 Hall and Jones (1999) and Caselli (2005) attribute most of the cross-country variation in levels of GDP per capita to TFP differences. Their measures of capital are cruder than the ones in EU KLEMS so the present finding can be taken as a useful confirmation of theirs. In fact, if the hypothetical capital elasticity which would reduce the cross-country differences in TFP levels to zero is estimated from the data in Hall and Jones (1999, Table 1), using the same model as above, its average value over all their 127 countries is 0.793. This compares with the value they assumed for the capital share, 1/3. The mean value of 0.793 is remarkably close to the mean value of 0.700 in Table 3.

cally. We can regress the growth of output per hour on the growth of capital per hour and check whether the coefficient on capital differs significantly from capital's share. This approach runs into well-known econometric difficulties since capital growth is likely correlated with the error term which includes TFP. Nevertheless, a model was estimated in which the current growth of labour productivity in the market sector depends on its own lagged growth rate and on the growth rate of capital per hour plus country and year controls. Both lagged productivity growth and capital per hour growth were highly significant. When estimated by OLS the long run capital elasticity was 0.42 and it was 0.40 when using the Arellano-Bond method. This is higher than the actual capital shares shown in Table 3 but not high enough to eliminate TFP as a source of growth.

TFP and the Solow model

In Solow's (1956) model, extended to include human capital, the long run growth rate of both output per hour and capital per hour is the TFP growth rate divided by the labour share, $\mu/(1-\alpha)$, plus the growth rate of labour quality.[22] In fact the actual labour productivity growth rate exceeds the rate predicted by the Solow model in 17 out of the 18 countries here; on average the actual rate is higher by 0.75 per cent per year (compare columns (3) and (5) of Table 3). The sole exception is Hungary. Also the growth of capital per hour exceeds that of labour productivity by on average 0.96 per cent per year; the only exceptions are Austria, Hungary, Ireland and Slovenia.

Two explanations come to mind. First, during a catch-up phase capital and labour productivity will grow faster in emerging economies than their long run rate. Against this we find actual growth exceeding the Solow prediction in mature economies as well as emerging ones and even in the United States which is not catching up to anyone. Second, the relative price of capital goods, particularly of ICT assets, has been falling in recent decades. So a two-sector model where the first sector produces consumer goods and some types of investment goods (e.g. buildings) while the second sector produces high-tech investment goods may be more appropriate (Whelan, 2001). In such a model the long run growth rate of capital exceeds that of output even though in value terms the capital-output ratio is constant. This is the case even for countries which import all their advanced capital equipment. Aggregate growth is still driven by TFP growth at home, but also by TFP growth abroad; the latter benefits capital-goods-importing countries via favourable changes in the terms of trade (Oulton, 2012).

Concluding Remarks

Based on an analysis of TFP growth in 10 industries within the market sector for 18 countries over the 1970-2007 period, drawn from the EU KLEMS dataset, we draw four main conclusions.

First, in all the countries considered here resources have been shifting out of agriculture and manufacturing, where TFP growth is high, and into finance and particularly business services where it is low. In fact, in business services TFP growth is measured to be on average negative in 17 out of the 18 countries studied. Despite this we conclude that structural change has probably been favourable to growth in most countries. The negative TFP growth in business services is very implausible. When this rate is set at the average rate in the market sector as a whole, with a corresponding downward adjustment in all other sectors to maintain the same

22 This can be seen from equation (6) after setting $\gamma = \alpha$, the capital share, and requiring that in the long run the growth of capital should equal the growth of output.

aggregate rate, structural change is found to favour growth in 11 out of the 18 countries.

Second, underestimation of quality change in capital goods could cause the role of TFP growth to be overstated and the role of capital to be correspondingly understated. And such underestimation, due to the failure of price indices for capital goods to fully reflect quality change, is plausible. But the upper limit for the effects of this mismeasurement seems to be fairly low, of the order of 0.35 per cent per year. At the aggregate level such an error is partially offset by a corresponding error in measuring the growth of output. However, at the industry level there is usually no such offset so here the effect on TFP is larger. Also the overstatement of TFP growth is larger in countries which import most of their high-tech capital goods.

Third, capital's role could also be understated if expenditure on some inputs is wrongly classified as intermediate consumption rather than as investment. The SNA now counts expenditures both on software and on R&D as investment where previously they were classified as intermediate. The net could be cast wider to include other types of expenditure on intangibles. But the evidence to date is that this will not reduce the importance of TFP in the growth process. This is because treating more inputs as investment changes the measurement of output as well as of capital.

Fourth, capital's role in the growth process would be larger if the elasticity of output with respect to capital were higher than capital's share, the latter being the standard growth accounting measure. This could be due to economies of scale, network externalities or to learning-by-doing. But we found that the increase in the elasticity necessary to reduce the role of TFP to zero was far too large to be plausible.

In summary, we have seen that any attempt to eliminate TFP from the growth story and replace it with some wider or better measure of capital seems unlikely to succeed. But we still have much to learn about TFP. Given the importance to TFP in growth theory and current fears of a pervasive growth slowdown (e.g. Cowen 2011; Gordon 2016), it is depressing that so much of the discussion still needs to be about measurement error. This is not the fault of the data compilers who are doing their best with limited resources. But though policy-makers everywhere are concerned about these issues, they are generally unwilling to devote the (quite limited) additional resources needed for improved measurement to advance understanding. Until this changes the mystery of TFP is likely to remain unresolved.

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