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Growth accounting with investment-specific technological progress: A discussion of two approaches

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Abstract

Two approaches taken to the embodiment question are compared and discussed: quantitative theory and traditional growth accounting. The two approaches give very different estimates for the contribution of investment-specific technological advance to economic growth. Therefore, the approach taken matters. It is argued that the measures used in traditional growth accounting to gauge the importance of investment-specific technological progress have little economic content, unlike the measure obtained from quantitative theory.

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1. Introduction

Should you use a model or not? That is a question often facing empirical researchers.

Models are used in macroeconomics in a wide variety of contexts. For questions about business cycles or growth, this frequently involves defining precisely the impulses affecting

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the economy, the propagation mechanism that maps these impulses into macro aggregates, a method for picking functional forms and parameter values, and a criterion to be used for matching the model with data. The demanded precision is a great thought-clarifying and -disciplining device. This approach is dubbed "quantitative theory", and has its roots in famous papers by Kydland and Prescott (1982) and Prescott (1986).

Traditional growth accounting takes a more structure-free approach, which does not depend upon functional forms or parameter values. This allows for more flexibility and, some believe, a greater degree of generality. A fully articulated general equilibrium model can be very cumbersome and specific. The method employed in traditional growth accounting was spawned by Solow's (1957) landmark paper. The assumptions required to use it are few: constant returns to scale, perfect competition, mobile factors, and the existence of either aggregate or sectoral production functions. Furthermore, it is elementary to implement. This approach has allowed economists to catalogue invaluable stylized facts about total factor productivity (TFP) at aggregate and sectoral levels, both within and across countries.

Whether or not one should take a structural or nonstructural approach to empirical questions often depends upon the issue at hand. The question of interest here is the contribution of investment-specific technological progress to economic growth. It is established that quantitative theory and traditional growth accounting report very different findings concerning the empirical importance of investment-specific technological progress for the growth process. Therefore, the approach adopted to tackle this question matters. So, which one should be used? It will be argued that quantitative theory is the preferred route to take for measuring the contribution of investment-specific technological progress to economic growth. The reason is that the measure advanced by quantitative theory to gauge the impact of investment-specific technological advance on economic growth has a well-defined economic interpretation. It uncovers the fraction of economic growth that results from investment-specific technological progress; i.e., the fraction of growth that would remain if other forms of technological progress were shut down. Traditional growth accounting cannot answer this simple question. Why? The reason is simple. Output growth derives from both technological advance and capital accumulation. Capital accumulation is partly driven by technological progress. Hence, in order to estimate the contribution of a particular form of technological progress to economic growth one must be able to make an inference about how much of capital accumulation was induced by this form of technological advance. Making such an attribution requires a complete structural model. In the absence of such a model, traditional growth accounting resorts to ad hoc measures with little economic content.

2. Greenwood et al. (1997)

This is an example of quantitative theory. The starting point for the analysis is the observation that the relative price of new equipment has shown tremendous decline over the postwar period. At the same time, the ratio of real equipment investment to real GDP rose. These two facts are at variance with the standard neoclassical growth model with just neutral technological progress, and suggest that it might be fruitful to look at technological progress in the equipment-producing sector. Thus, the exercise is guided from the very beginning by the comparison of predictions from economic theory with the data. There are two impulses in the model: the rates of investment-specific (or capital-embodied) technological progress, $\hat{q}$, and neutral (or disembodied) technological change, $\hat{z}$.[1] The propagation mechanism is the neoclassical growth model. In its one-sector version, the technological structure considered can be summarized by

$$c + i = y = zf(k, l), \tag{1}$$

and

$$\dot{k} = qi - \delta k. \tag{2}$$

Here c and i denote consumption and investment in units of consumption, and q represents the number of units of new capital that can be manufactured from a unit of final output. The structure has its roots in Solow's (1960) classic paper. Given this setup, the relative price of investment goods, p, is equal to $1/q$. Therefore, on the left-hand side of (1) everything is expressed in units of consumption, the numéraire. Note that in (2) the quantities $\dot{k}$, qi, and k are all expressed in efficiency units of capital.

Over long periods of time, labor's share of income has been relatively constant. In light of this observation, assume that production is governed by a Cobb–Douglas production function, or that

$$zf(k, l) = zk^{\alpha} l^{1-\alpha} \quad \text{for } 0 < \alpha < 1. \tag{3}$$

Solow (1957, p. 319) showed that this functional form fits the long-run data well. Along a balanced growth path output measured in consumption units, or y, grows at the rate g given by $g = (\hat{z} + \alpha\hat{q})/(1 - \alpha)$.[2] The contribution of investment-specific technological advance to output growth is then

$$\frac{\alpha\hat{q}}{\hat{z} + \alpha\hat{q}}. \tag{4}$$

The above expression can be used for growth accounting. Eq. (4) has a clear interpretation in terms of the theory developed. It gives the fraction of long-run growth that would remain if all neutral technological advance is shut down ($\hat{z} = 0$). In other words, it gives the fraction of long-run growth due to investment-specific technological progress.[3] To use this equation, all one needs to know is α, $\hat{q}$ and $\hat{z}$. In the analysis, investment-specific technological progress, $\hat{q}$, can be identified from observations on the change in the relative price of investment goods.[4] The parameter α can be pinned down using observations on capital's share of income. Neutral technological progress, $\hat{z}$, can be

[1] Oulton's (2006) notation is used throughout the paper. A '^' over a variable denotes its rate of change while a '·' signifies just its change (or a time derivative).

[2] To ensure balanced growth, Greenwood et al. (1997) also assume that agents in the economy have preferences that are logarithmic in consumption and leisure. These preferences are presented later—see Eq. (8).

[3] This thought experiment can be implemented in more general models with investment-specific technological progress where a closed-form solution along the lines of (4) may not exist. The only requirement is that the model is computable. If so, then one can shut down neutral technological progress and calculate numerically what happens to economic growth. Additionally, it does not require the assumption of balanced growth. One just needs to be able to compute the transitional dynamics for the economy in question. Thus, the idea is quite general.

[4] The ability to identify q with $1/p$ depends on the structure adopted. For example, Hornstein and Krusell (1996) show within the context of a two-sector growth model that if capital's share is lower in the investment sector than in the consumption sector, which seems to hold true in the data, $\widehat{q}$ must be bigger than $-\widehat{p}$. Therefore, the rate of investment-specific technological advance would be even higher than the rate of price decline in this case.

measured residually via (2) and (3). The analysis concludes that about 58% of postwar growth in the last century is due to investment-specific technological progress.

3. Oulton (2006)

Oulton (2006) contends that traditional growth accounting can be used to come up with a measure of the contribution of investment-specific technological advance to economic growth. Oulton (2006) does *not* argue that the traditional growth accounting approach or measure is better or worse than the one presented in Greenwood et al. (1997). In fact, he motivates his measure using a two-sector model similar to the one presented in Greenwood et al. (1997, Section V.A). To gauge the contribution of investment-specific technological progress to economic growth, Oulton [2006, Eq. (20)] proposes the following measure:

$$\frac{s\widehat{q}}{\widehat{z}+s\widehat{q}}, \tag{5}$$

where s is the share of investment in output as given by $s = i/(c+i)$. In a formal sense, then, (5) is traditional growth accounting's substitute for (4). The two formulae look very similar; in (5) s replaces the α that is in (4). This difference turns out to be important.

3.1. Accounting practice matters

Does it matter whether (4) or (5) is used to measure the contribution of investment-specific technological progress to economic growth? The answer is yes, as Table 1 shows. First, note that Oulton's formula results in a *very* different finding than the Greenwood et al. one, for a given set of estimates on α, $\widehat{q}$, s, and $\widehat{z}$. Oulton presents two sets of estimates for these inputs, to wit Greenwood et al.'s and his own. Take the findings based upon the Greenwood et al. (1997) estimates, as given by the first column (of numbers) in the table. Eq. (4) yields an answer of 58% versus the 38% derived from (5), a difference of 20 percentage points.[5] Hence, the contribution of investment-specific technological progress to growth is about 1.5 larger using (4) versus (5). Mechanically speaking, it arises because capital's share of income, α, is larger than the share of investment in output, s.[6] Oulton's (2006, abstract) statement that "the differences between [Greenwood et al.'s (1997)] conclusions and those of growth accounting studies about the extent to which embodiment explains U.S. economic growth are found to relate more to data than to methodology" is therefore hard to understand.[7]

3.1.1. The definition of output

The definition used for output will matter for calculating the contribution of investment-specific technological progress to aggregate output growth. Greenwood et al. (1997)

[5]Note that in the Greenwood et al. (1997) model the capital stock is broken down into equipment and structures. Investment-specific technological progress is assumed to affect equipment only. Thus, rather than (4) the actual formula used is $\alpha_e\widehat{q}/(\widehat{z}+\alpha_e\widehat{q})$, where α_e is the exponent on equipment in a Cobb–Douglas production function. Likewise, in (5) s should be replaced by s_e, or the Domar weight on equipment.

[6]Even when using Oulton's (2006) estimates for α, $\widehat{q}$, s, and $\widehat{z}$ the difference is 11 percentage points, with the Greenwood et al. (1997) measure yielding a number about 1.4 larger than Oulton's—see the last column in the table. So, the measure used clearly matters.

[7]In the quote the word "their" has been replaced with "Greenwood et al. (1997)".

Table 1
Contribution to growth

	Data—α, $\widehat{q}$, s, $\widehat{z}$	
Measure—Eqs. (4), (5) and (7)	Greenwood et al.	Oulton
Greenwood et al.—Eq. (4), consumption based	0.58[a]	0.37[a]
Oulton—Eq. (5)	0.38[a]	0.26[a]
Greenwood et al.—Eq. (7), Divisia index based	0.65	0.45

[a]Source: Oulton (2006, Table 1).

measure output in nondurable consumption units. Eq. (4) is predicated upon this definition. In the context of the standard neoclassical growth model, where nondurable consumption and leisure are the only goods consumed, the consumption-based output measure is the most natural one to use.[8] This will be discussed latter on. Traditional growth accounting uses a Divisia index for tallying output growth. So, alternatively suppose in line with traditional growth accounting that aggregate output growth is calculated using a Divisia index. How will this change the Greenwood et al. (1997) estimate of the contribution of investment-specific technological advance to output growth? Does the gap between the Greenwood et al. and traditional growth accounting measures grow larger or smaller?

A virtue of quantitative theory is that it specifies a precise way for mapping theory into *any* desired measure of output. To see this define the rate of growth in output using the Divisia index, $\widehat{Y}$, by

$$\widehat{Y} = (1 - s)\widehat{c} + s\widehat{qi}, \tag{6}$$

where again s is investment's share of output.[9] In the Greenwood et al. (1997) framework it happens that along a balanced path $\widehat{c} = [\widehat{z} + \alpha\widehat{q}]/(1 - \alpha)$ and $\widehat{qi} = [\widehat{z} + \widehat{q}]/(1 - \alpha)$ so that

$$\widehat{Y} = \frac{\widehat{z} + (1 - s)\alpha\widehat{q} + s\widehat{q}}{1 - \alpha} > \frac{\widehat{z} + \alpha\widehat{q}}{1 - \alpha} = g \quad (\text{when } \widehat{q} > 0).$$

Output growth using the Divisia index, $\widehat{Y}$, is higher than the consumption-based one, g.

It is then easy to see that contribution of investment-specific technological progress to growth using a Divisia index is

$$\frac{(1 - s)\alpha\widehat{q} + s\widehat{q}}{\widehat{z} + (1 - s)\alpha\widehat{q} + s\widehat{q}}. \tag{7}$$

This formula is the analogue to (4) when a Divisia index is used. Note that it is *not* the same conceptual measure as is proposed by Oulton (2006), as given by (5). This is what does the job, though; it maps the predictions of the theory into the Divisia index. It gives the fraction of $\widehat{Y}$ that is due to investment-specific technological progress. Observe that

$$\frac{(1 - s)\alpha\widehat{q} + s\widehat{q}}{\widehat{z} + (1 - s)\alpha\widehat{q} + s\widehat{q}} > \frac{\alpha\widehat{q}}{\widehat{z} + \alpha\widehat{q}},$$

[8]For a detailed discussion on the appropriateness of different output measures, see Hornstein and Krusell (2000).

[9]Whelan (2003, p. 644) notes that growth in chain-weighted GDP is well approximated by a Divisia index.

because the left-hand side is increasing in $(1-s)\alpha\widehat{q}+s\widehat{q}$ when $\widehat{z}$ is positive, and $(1-s)\alpha\widehat{q}+s\widehat{q}>\alpha\widehat{q}$ for all $\alpha, s \in (0,1)$ and $\widehat{q}>0$. The left-hand side of the above expression gives the contribution of investment-specific advance to growth when output growth is defined using a Divisia index, while the right-hand side represents the same thing when output growth is denominated in consumption units. Hence, measure (7) will report that investment-specific technological progress accounts for a *larger* fraction of long-run growth than will (4). Thus, the estimate used in Greenwood et al. (1997) is a *conservative* one—*cf*. Greenwood et al. (1997, Section IV).

Therefore, the gap between the Greenwood et al. (1997) measure and the traditional growth accounting one will widen when a Divisia index is used to measure output growth. By how much, is the natural question. Using the Greenwood et al. estimates for the inputs into Eq. (7) results in 65% of growth (see the third row in the table) being attributed to investment-specific technological progress![10] This is 1.7 times larger than the 38% found using the traditional growth accounting measure.[11] Once again, accounting practice clearly matters. Overall the measures used by Greenwood et al. and traditional growth accounting to gauge the importance of investment-specific technological progress to growth give very different estimates, even when the same data inputs (for α, $\widehat{q}$, s, and $\widehat{z}$) are used.

3.2. The importance of the data used for the price of investment goods

When measuring the contribution of investment-specific technological progress to economic growth it will indeed matter what estimates for α, $\widehat{q}$, s, and $\widehat{z}$ are inputted into the formulae (4), (7) and (5). This point is trite, theoretically speaking. It matters quantitatively as a comparison across the last two columns in Table 1 shows. The set of estimates obtained for α, $\widehat{q}$, s, and $\widehat{z}$ depends upon whether or not one uses Gordon's (1990)—or other—quality adjustments to the relative price series for investment.

Recall that in the Greenwood et al. (1997) framework the relative price of investment goods, p, can be used to identify q, because $q=1/p$ so that $\widehat{q}=-\widehat{p}$. Greenwood et al.'s (1997) estimates are based on Gordon's (1990) data for the price of investment goods, while Oulton's (2006) estimates are predicated upon standard National Income and Product Accounts (NIPA) data. Hercowitz (1998, Figure 1) illustrates that Gordon's (1990) quality-adjusted price declines at a faster clip than the traditional NIPA one. Oulton (2006) does not challenge, however, the use of Gordon's (1990) data. It is also used in traditional growth accounting exercises, such as Hulten (1992). Which measure should be

[10]The formula used is

$$\frac{(1-s_e)\alpha_e\widehat{q}+s_e(1-\alpha_s)\widehat{q}}{\widehat{z}+(1-s_e)\alpha_e\widehat{q}+s_e(1-\alpha_s)\widehat{q}},$$

where α_e and α_s are the exponents on equipment and structures in a Cobb–Douglas production function, and s_e is the Domar weight on equipment. For the Greenwood et al. (1997) estimates input into the above formula $\alpha_e=0.17$, $\alpha_s=0.13$, $\widehat{q}=0.032$, $s_e=0.073$ and $\widehat{z}=0.0039$, while for the Oulton (2006) ones use $\alpha_e=0.17$, $\alpha_s=0.13$, $\widehat{q}=0.012$, $s_e=0.101$, and $\widehat{z}=0.0036$. Two caveats are in order: (i) the parameters α_e, α_s, $\widehat{q}$, and $\widehat{z}$ should really be re-calibrated and -estimated, along the lines of Greenwood et al. (1997), using chained-indexed GDP data instead of the consumption-denominated data while still using Gordon's (1990) price index for new equipment; (ii) s_e is endogenous in (7) and therefore should be allowed to change when $\widehat{z}$ is set to zero. The above shortcuts are taken to make the comparison with Oulton (2006) easier.

[11]Alternatively, take Oulton's (2006) estimates. Investment-specific technological advance then accounts for 45% of growth, which is much larger (1.7 times) than the 26% returned by traditional growth accounting.

used? It is likely that the NIPA underestimate the rate of price decline in durable goods. Recent work by Bils (2004) finds that the Bureau of Labor Statistics, as a consequence of the difficulties of taking into account quality change, seriously overestimates the rate of price increase in durable goods. He (p. 4) finds "that average quality growth for durables has likely been understated by 3% per year, or more, during the past 15 years." [Bils (2004) does not use hedonic pricing, unlike Gordon (1990).]

4. Which accounting practice should be used?

It has been established that the approach taken to growth accounting with investment-specific technological advance matters in a quantitative sense. Which one should be used then? That is, should (4) or (5) be used to measure the contribution of investment-specific technological progress to economic growth? It is hard to see what the economic content of (5) is: it does not appear to be the answer to any meaningful economic question. It simply mechanically tabulates the share of investment-specific technological progress in (Divisia-output-based) aggregate TFP growth, where the latter is defined to be a weighted average of sectoral TFP growth rates or $(1-s)\widehat{z}+s(\widehat{zq})=\widehat{z}+s\widehat{q}$. It does *not* give the fraction of *economic growth* that is due to investment-specific technological progress. Why? The answer is that growth in output derives from two sources, viz technological progress and capital accumulation. Thus, in order to break down the contributions that the two sources of technological progress make to output growth, one has to know how much of the growth in the capital stock can be ascribed to the two forms of technological progress. Such an inference requires an economic model. Thus, the usefulness of a measure such as (5) is questionable.

Perhaps (5) provides a better measure of the changes in welfare over time than does (4)? As in Greenwood et al. (1997), define period-t lifetime utility, U_t, by

$$U_t=\theta\int_0^\infty \ln c_{t+s}\mathrm{e}^{-\beta s}\,\mathrm{d}s+(1-\theta)\int_0^\infty \ln(1-l_{t+s})\mathrm{e}^{-\beta s}\,\mathrm{d}s, \tag{8}$$

where c_{t+s} and l_{t+s} are period-$(t+s)$ nondurable consumption and hours worked. Along a balanced growth path, c_{t+s} grows at the same constant rate as output, $g=(\hat{z}+\alpha\hat{q})/(1-\alpha)$. Hours worked will be constant, say at some level l^*. Hence, under balanced growth period-t lifetime utility is given by

$$U_t=\theta\ln c_t/\beta+\theta g/\beta^2+(1-\theta)\ln(1-l^*)/\beta. \tag{9}$$

It is easy to see that $\mathrm{d}U_t/\mathrm{d}t=\theta g/\beta$, so that the change in lifetime utility over time is connected to the growth rate in output measured in consumption units. Therefore, within the rarefied atmosphere of the model, the growth rate of output in consumption units is a *perfect* measure of the change in welfare over time.

If one prefers not to measure welfare changes in utils then imagine two economies in balanced growth. Let the first economy grow at rate g and the second at rate $g'<g$. The second economy is the same as the first, but with investment-specific technological progress shut down. For simplicity, let consumption in the baseline period t be the same in both economies. People in the second economy work some constant amount $l^{*\prime}$. How much would a person have to be given in terms of consumption in order to be enticed to move from the first economy to the second? To answer this question, let e^λ represent the factor by which period-t baseline consumption in the second economy would have to be raised so

that a person would be indifferent to the move. It is easy to calculate using (9) that

$$\begin{aligned}\lambda &= (g-g')/\beta + [(1-\theta)/\theta]\ \ln[(1-l^{*})/(1-l^{*\prime})]\\ &= [\alpha\hat{q}/(\hat{z}+\alpha\hat{q})]g/\beta + [(1-\theta)/\theta]\ \ln[(1-l^{*})/(1-l^{*\prime})]. \end{aligned} \tag{10}$$

In this welfare calculation it is again expression (4) that appears, and not (5) or any other expression. Quantitative theory provides a clear mapping from measures of technological progress into welfare. [Note that tastes are never given in Oulton (2006).] The details of this mapping will change as the model changes, such as when consumer durables are added—see Whelan (2003).[12]

To conclude, the approach taken to growth accounting with investment-specific technological progress matters in a quantitative sense. Therefore, the approach is important. Economic theory should guide the choice between the two approaches. The traditional growth accounting concept advocated by Oulton (2006) is hard to interpret in an economically meaningful way.

5. Conclusion

Back to the question posed at the beginning. Which method yields the highest returns to studying the importance of investment-specific technological advance for economics? Both methods have been used to obtain estimates of the contribution of investment-specific technological progress to economic growth, or to catalogue stylized facts. The estimates differ, so the approach taken matters. Take the quantitative theory approach first. By comparing the predictions of models with the data, it is clear that technological progress in the capital goods sector might be an important source of growth. The quantitative theory approach puts great discipline on the search for how much. It provides a mapping between investment-specific and neutral technological advance, on the one hand, and observables such as output and the relative price of new capital goods, on the other. This is not without some cost, though, because the estimates will depend to some extent upon the details of the structure employed. As Solow (2001, p. 177) says, "The idea of a dichotomy between measuring and modelling is breaking down" and "(p)rogress in measuring and understanding investment-specific or capital-embodied technical change will then be tied up with different stories about the way the economy functions." In short, you cannot get something for nothing.

Turn now to traditional growth accounting. Solow's (1957) paper showing how to obtain a measure of disembodied technological progress in a more or less structure-free way is simply brilliant. It allows for the invaluable cataloguing of stylized facts about TFP, both across time and space. However, disenchanted with the notion of disembodied technological progress, Solow (1960) wrote another ingenious paper arguing that technological advance is embodied in the form of new and improved capital goods.[13] It met with little success; (Solow, 2001, p. 175) has remarked that he "liked the idea, but it

[12]In general, a simple solution for the change in welfare, such as that given in (10), may not exist. Provided that the model is computable a numerical solution for the change in welfare can be calculated along the above lines.

[13]To quote Solow (1960, pp. 90–91) on the concept of disembodied technological advance: "It is as if all technical progress were something like time-and-motion study, a way of improving the organization and operation of inputs without reference to the nature of the inputs themselves. The striking assumption is that old and new capital equipment participate equally in technical change. This conflicts with the casual observation that many if not most innovations need to be embodied in new kinds of durable equipment before they can be made

went nowhere." Part of the reason was that it was challenged by Jorgenson (1966, pp. 8 and 11) who said "one can never distinguish a given rate of growth in embodied technical change from the corresponding rate of growth in disembodied technical change." In addition, Jorgenson (1966, Sections I and V) alluded that it is not even important for economics to make such a distinction between the two forms of technological advance.

So, the idea of capital-embodied technological progress languished in the traditional growth accounting literature until Hulten (1992) attempted to revive it. He used observations on the relative price of new capital goods to construct a measure of the capital stock in efficiency units, and thereby come up with an index of embodiment by comparing this capital stock with the conventionally measured one. Hulten then harnessed this index of embodiment to the traditional growth accounting apparatus to produce an estimate of the importance of embodiment for economic growth. Oulton (2006) illustrates how a measure of embodiment can be obtained in a more standard manner. In either case, though, the traditional growth approach still fails to answer the most apropos question: How much of economic growth is accounted for by investment-specific technological progress? The problem is that economic growth derives from two basic sources, to wit technological progress and capital accumulation. Capital accumulation results from technological progress. Without an economic model, it is impossible to allocate capital accumulation across the underlying causal sources of technological advance. Forty-five years after Solow's (1960) paper, the profession expects more. The history of the search for embodiment is a prime example of why theory should be connected with measurement.

In traditional growth accounting estimates of investment-specific or neutral technological progress are themselves the end goal. For quantitative theory it is just the beginning. The fact that a large portion of technological progress is embodied in new capital goods may have implications that warrant further research. For example, suppose that capital substitutes for unskilled labor in the market place. Investment-specific technological progress may be associated with a rise in the skill premium. Or alternatively, suppose that it substitutes for labor at home. Then, it might lead to an increase in female labor-force participation. In fact, the adoption of new technologies over time may be influenced by a country's cost of skilled and unskilled labor. Countries where unskilled labor is relatively inexpensive may adopt different technologies compared to ones where it is expensive. Therefore, measures of productivity may have an endogenous component in them. Indeed, these very questions are already being addressed by quantitative theory.

6. Postscript: Jorgenson (1966)

Greenwood et al. (1997, Section III) compare their approach to the one taken by traditional growth accountants, as exemplified by Hulten (1992). Hulten (1992) replaces (1) with

$$c + qi = zf(k, l), \tag{11}$$

while retaining (2). The difference between (1) and (11) is that on the left-hand side of the latter, consumption and investment are measured in their own 'quality-adjusted' units as

(*footnote continued*)
effective. Improvements in technology affect output only to the extent that they are carried into practice either by net capital formation or by the replacement of old-fashioned equipment by the latest models…"

opposed to being valued in terms of consumption.[14] Hulten (1992, p. 967) attributes this framework to Domar (1963) and Jorgenson (1966). Oulton (2006) vehemently disputes this attribution because "(n)either in the cited 1966 article nor elsewhere in his extensive empirical work does Jorgenson rely on an aggregate production function of the form" used in the above equation.

This is purely a doctrinal dispute. It is true that no aggregate (or *any* other) production function appears in Jorgenson (1966)—this includes Oulton's (2006) sectoral ones. Jorgenson's (1966) paper must be viewed within the context of the time: it is an attack on Solow's (1960) embodiment hypothesis, which uses a one-sector growth model. What exactly Jorgenson had in mind must be interpreted from the text since, unlike in Solow (1960), a complete and well-specified economic model is *not* spelled out. At the outset, though, Jorgenson states (1966, p. 1) that "changes in the index of TFP may be interpreted as shifts in an aggregate production function or as 'disembodied' technical change." When discussing Solow's (1960) one-sector model with embodied technological progress, Jorgenson (1966, p. 10) clearly suggests that investment should be measured in quality-adjusted units, in addition to the capital stock. Domar (1963, p. 586) also mentions that final output should be adjusted for quality improvement in the production of new capital. Therefore, the attribution by Hulten (1992) of (11) and (2) to Domar (1963) and Jorgenson (1966) seems appropriate.

A separate question is whether or not Oulton's (2006) analysis is in the spirit of the Jorgenson (1966). Specifically, is Oulton (2006) a modern transliteration of Jorgenson (1966)? The answer is no. Ironically, Jorgenson states (1966, pp. 8 and 11) that "one can never distinguish a given rate of growth in embodied technical change from the corresponding rate of growth in disembodied technical change." Thus, his 1966 conclusion is at *sharp variance* with Oulton's (2006) one that you *can* distinguish between these two forms of technological progress using traditional growth accounting. Therefore, it is clear that Jorgenson (1966) could *not* have had Oulton's (2006) setup in mind—unless Oulton is silently taking the view that Jorgenson made a logical error between the assumptions and conclusions.

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[14]Though appearing here in level form in a resource constraint, quality adjustment is often implemented in terms of accounting identities involving rates of change—see Jorgenson (1966) for an early discussion.

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