On the Role of Embodied and Investment–Specific Technological Change in the New Economy: A Survey

Huw Lloyd–Ellis
Department of Economics
Queen's University
Kingston, Ontario
Canada K7L 3N6
lloydell@qed.econ.queensu.ca

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Abstract

This article surveys the literature surrounding the ongoing debate as to the importance of embodied technical change (ETC) and investment–specific technological change (IST) in driving labour productivity growth. In particular, it emphasizes that (1) ETC and IST are distinct concepys, (2) the measurement of the rates of both ETC and IST are problematic, (3) the measured importance of IST depends crucially on the macroeconomic accounting framework used and the appropriate concept of GDP, and (4) its importance also depends on behavioural assumptions. I also assess the extent to which recent productivity movements can be attributed to IST and the implications for forecasting future productivity.

1 Introduction

Despite significant investment in computers and other information technology, Canadian and US labour productivity growth from the mid–1970s to the early 1990s failed to achieve the levels observed in the 3 decades immediately following World War II.[1] The apparent productivity revival during the late 1990s, coupled with an unprecedented growth in IT related stock prices, led many pundits to proclaim the long–awaited arrival of the "new economy". However, other observers such as Gordon (1999), argued that this productivity revival was in large part cyclical. Moreover, any more permanent increases were almost entirely concentrated in industries producing IT related equipment, and very few "spillovers" could be seen in the rest of the economy. To the extent that Canada relies on technological spillovers from the US, the apparent absence of this broader impact of IT investment is especially worrying.[2] The subsequent crash of technology stocks, the economic slowdown, and the recent downward revision of 1990s productivity growth estimates in the US, have all dealt a blow to the view that some permanent, structural change has occurred that will enhance long–run productivity growth.

In understanding growth in labour productivity, a crucial distinction must be made between growth that is due to capital formation (in its broadest sense) and growth that is due to improvements in technology (i.e. shifts in the production possibilities frontier). The former source of growth is costly in that it requires the economy to forego current consumption in return for future consumption. The latter source is typically viewed as costless: either a kind of "manna–from–heaven" or, perhaps, reflecting dynamic spillovers from past activities. Generally speaking, the empirical growth economist has had two main tasks: first, to undertake the enormous job of constructing historical data on inputs and outputs: and second to measure the degree to which output growth is in fact due technological factors and how much should be assigned to capital formulation. A vast empirical literature has attempted to sort out the capital–technology dichotomy, but no clear consensus has emerged. Many of the early studies favoured productivity as the main explanation of output growth (see Griliches, 1996). However, Jorgenson and Griliches (1967) famously disagreed, and their alternative view finds support in subsequent work (e.g. Young, 1995) and the New Growth literature.

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[1] This observation inspired Robert Solow's (1987) famous quote that "we can see the computer age everywhere but in the productivity statistics".

[2] Although, US investment in machinery and equipment rose steadily from 6% to 8% of GDP since the 1960s, in Canada it has remained relatively constant, and in the 1990s was still about 6%.

The distinction between capital formation and technological change is important in interpreting movements in labour productivity over the last few decades, because in large part the technological improvements associated with the new economy have been embodied in the equipment capital stock (e.g. computers, internet hardware, etc.). Some productivity analysts (most notably Jorgenson and Stiroh, Jorgenson, etc.) argue that these improvements have been part of the process of costly capital formation and do not, as yet, reflect major economy–wide shifts in production possibilities, as typically envisaged by new economy pundits. Moreover, although productivity growth in equipment–producing sectors became a more important part of overall productivity growth in the late 1990s (Oliner and Sichel, 2000, Jorgenson and Stiroh, 2000), there appears to have been little effect in the rest of the US economy.

An alternative viewpoint, however, is that these improvements reflect rapid **investment–specific technological change (IST)**, especially since the mid–1970s, which has significantly reduced the cost of producing new investment goods relative to consumption goods. According to this view, the acceleration in IST has been “hidden” in aggregate statistics because of a dramatic slowdown in productivity growth from other sources (e.g. human capital accumulation). While the acceleration in labour productivity growth during the late 1990s largely reflected capital deepening, according to this view, much of this was the result of exogenous IST which enhanced the productivity of each unit of foregone consumption (or foregone investment in other sectors) invested in IT sectors. This is interpreted as a widespread effect which has shifted the productive possibilities of the economy.

In this article, I discuss how these alternative interpretations depend crucially on three interrelated issues:

- Measurement of components of the real effective capital stock — As is well understood by now, official price statistics can be very misleading when used to determine real effective investment. This is because they do not properly take into account quality improvements which increase the effectiveness of a “natural” unit of capital. Recent advances in hedonic pricing techniques have improved the measurement of some kinds of capital, but there is disagreement about how to interpret the implied relative price movements.
- Aggregation of consumption and investment goods to compute aggregate GDP growth — Two competing classes of macroeconomic accounting framework exist, one based on the early work of Domar (1963) and Jorgenson (1966) and the other based on that of Solow (1960). In the

presence of IST, the implications of these to frameworks can diverge in subtle ways that lead to very different interpretations of recent events.

• Equilibrium effects — Conventional productivity accounting frameworks typically treat factor allocations across sectors as being exogenous. Many analysts have for a long time advocated taking into account the endogenous impacts of technological change on economic decision making. Recently, Greenwood, Hercowitz and Krusell (1997) have argued that when one does this, the importance of IST may be significantly magnified as a source of overall productivity growth. However, their approach has come under significant criticism.

These issues also bear upon the recent evidence as to whether there has been some kind of structural change in the 1990s that we might associate with the "new economy", or whether it was just an unusually long cyclical expansion. Official statistics do appear to indicate an acceleration in US labour productivity growth between 1995–1999, beyond that which would usually be associated with cyclical upturns (as measured by the drop in the unemployment rate, for example). However, the conclusions are sensitive to the measurement issues noted above, and it is not clear how widespread this acceleration has been. Getting the decomposition between trend and cycle right has important implications for forecasts of future productivity growth, and hence for both monetary and fiscal policy.

This article is laid out as follows. In Section 2, I discuss the distinction between embodied technical change and investment–specific technological change, and the alternative methods that have been employed to measure them. In Section 3, I discuss the two alternative accounting framework that have been used to decompose labour productivity growth into its various components and show how they have led to differing interpretations of changes that have occurred since the 1970s. In particular, I identify the failings of each framework and assess their implications. Section 4 discusses a number of other important measurement issues relating to the debate and discusses how adjustment for them is likely to affect the conclusions. Section 5 goes on to evaluate the recent evidence that has attempted to determine whether a structural change in the forces driving productivity growth occurred during the 1990s. Finally, section 6 highlights the issues involved in forecast the implications of technological change, and in particular IST.

2 Estimating the Rates of Embodied and Investment–Specific Technological Change

2.1 Embodied Technological Change

2.1.1 Price–Based Estimates

Embodied technological change refers to improvements in the quality of investment goods. We start from the observation that the services of new and old capital should be measured in terms of **efficiency units** (e.g. computing power) rather than "natural units" (e.g. number of PCs).[3] One way to represent efficiency units of new investment goods is to define it as

$$e_t = Q_t I_t, \tag{1}$$

where Q_t is a quality index and I_t denotes real investment in natural units. Quality can, in principle, be measured as the ratio of a (hedonic) price index, p_{et}, for efficiency units of capital (e.g. the price of a unit of RAM) and a price index, p_{It}, for natural units (e.g. the price of a PC). To see this, note that the nominal value of investment goods must be the same whether we think of them in natural or efficiency units

$$p_{et} e_t = p_{It} I_t \tag{2}$$

Substituting for e_t using (1) and re–arranging yields

$$Q_t = \frac{p_{It}}{p_{et}}. \tag{3}$$

Example: Suppose the price of a PC in 1990 were \$10,000 and the price of one in 1980 was \$5,000. A simple price index, p_I, would be doubled. However, the 1990 PC is very different from the 1980 PC: it is likely hugely more powerful and much faster. A more meaningful price index for efficiency units would value these characteristics separately (this is the basic idea of "hedonic pricing" and is equivalent to expressing investment goods in "efficiency units"). Thus, if the 1990 PC were twice as powerful and twice as rapid as the 1980 PC, then a 1990 PC would be equivalent (in terms of efficiency units) to two 1980 PCs. The nominal price of an "efficiency unit" of PCs would remain unchanged, but the quality of the capital stock would have doubled.

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[3] There is no conceptual reason why labour inputs cannot be defined in terms of "efficiency units" of human capital. However, the focus here is on physical capital, so increments in human capital are subsumed into the residual technology parameter.

To compute such an index requires knowledge of the contribution of the various characteristics of the unit of capital to its marginal product and hence its price. Such a price index can be obtained through hedonic pricing techniques. However, this generally requires a large amount of information on the characteristics of many different kinds of capital, much of which is unavailable. Thus, any estimated price index is subject to various criticisms: e.g. omitted characteristic bias, lack of coverage, etc. Following the study of Cole, et al. (1986), which estimated a high quality–improvement component (between 10 and 20% per year) in the price of computers, the U.S. Bureau of Economic Analysis (BEA) revised its treatment of computers in the National Income and Product Accounts (NIPA). While the magnitudes are less dramatic, Gordon (1990) reports a substantial quality component in a wide range of producers' durable–equipment prices. Hulten (1992) uses Gordon's hedonic price series divided by the non–quality adjusted index produced by the BLS, in order to compute the growth rate of Q_t. He finds that the rate of embodied technical change, $\hat{Q}$, for the investment goods in question, averaged 3.44% per annum from to.1949 to 1983.

What does this imply for the stock of effective capital used in production ? New investment goods are added to a depreciated stock of capital services and used in production. Assuming a constant rate of physical depreciation, δ, a measure of the aggregate efficiency units of capital stock available for use in production can be constructed according to the perpetual inventory method:

$$h_{t+1} = (1 - \delta)h_t + e_t, \tag{4}$$

where h_0, the initial capital stock, is assumed to take on the steady–state level.[4] In this way quality improvements are **embodied** in the stock of capital services. Note that the resulting measure of the stock of capital therefore depends crucially on the depreciation rate and the evolution of the measured quality index. Let efficiency units of capital services be given by

$$h_t = B_t k_t, \tag{5}$$

where B_t is an index of the quality of the existing capital stock and k_t denotes the capital stock in natural units, net of depreciation. The latter evolves according to

$$k_{t+1} = (1 - \delta)k_t + I_t, \tag{6}$$

Growth in B_t is referred to as the rate of **average embodied efficiency** or **growth in the quality of the capital stock**, and it will generally be lower than the rate of embodied technical

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[4] That is $h_0 = e_0/\delta$. In practise, proper accounting must allow for variation in depreciation rates across types of capital and across time. For expositional simplicity, I ignore these issues here.

change.[5] Hulten (1992) computes the implied rate of embodied technical change as the difference in the growth of the capital stock in efficiency units and that in natural units:

$$\hat{B} = \hat{h} - \hat{k}. \tag{7}$$

The evolution in the capital stock are computed for each type of capital according to (4) and (6). The aggregate growth in the capital stock is measured as the share–weighted average of the various types of capital. Hulten estimates the rate of growth of average embodied efficiency to be approximately 3%. This implies that over the 1949–83 period, the quality of new investment goods exceeded the average level by about 23%.

2.1.2 Production–Based Estimates

In general, obtaining hedonic prices for all capital services is difficult. As Jorgenson (2001, p.8) points out "evidence on the prices of communications equipment and software is seriously incomplete, so that official price indexes are seriously misleading." Moreover, Hornstein and Krusell (1996), Gort and Wall (1998) and others argue that price–based estimates of embodied technical change are likely to significantly understate the true rate. In the absence of a sufficiently broad and accurate hedonic price index, some other approach must be used to measure the changes in the quality of the capital stock. An alternative approach, first derived by Nelson (1964) is to use the age structure of the capital stock to infer the growth in the quality of the capital stock. Assuming that the rate of embodied technical change, $\hat{Q}$, is constant, Nelson's (1964) approximation of the level of average embodied efficiency is

$$B_t \simeq Q_t \exp\left(-\frac{\hat{Q}}{\delta}\bar{a}_t\right), \tag{8}$$

where $\bar{a}_t$ represents average age of the capital stock in place.[6]

Assuming the approximation in (8) is sufficiently accurate, one could then use disaggregated data to estimate the sensitivity of output to the age of the capital stock. Assuming a Cobb–Douglas production function at the plant/firm level, for example, one could estimate the following production relationship:

$$\log y_{it} = \beta_0 + \beta_1 t + \beta_2 \log l_{it} + \beta_3 \log k_{it} + \beta_4 \bar{a}_{it} + \varepsilon_{it}, \tag{9}$$

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[5] Growth in h is often referred to as capital–deepening.

[6] See appendix for derivation.

where y_{it}, l_{it} and k_{it} denote the time t output, labour and capital used by firm i and the $\beta_j's$ are parameters to be estimated.[7] Under the null hypothesis of significant embodied technical change, $\beta_4 < 0$, and the implied estimate of the rate of embodied technical change would be

$$\hat{Q} = -\delta\hat{\beta}_4. \tag{10}$$

If output were insensitive to age, then the rate of embodied technical change would be insignificantly different from zero. This approach is, of course, subject to the usual econometric problems associated with simultaneity biases, etc.

Production–based estimates of embodied technological change have a long history which predates the price–based estimates. For example, Gregory and James (1973) follow such an approach and find little evidence to support the view of rapid embodied technical change. More recently, Baily and Gordon (1988) have argued that embodied technical change cannot be adduced as an explanation of the 1970's productivity slowdown. However, in a study a sample of young manufacturing plants, Bahk and Gort (1993) find that a 1–year drop in the average age is associated with a 2.5–3.5 % rise in the plant's gross output. This corresponds to a 15–21% annual rate of embodied technical change.

It is not clear how good an approximation is given by (8), and how sensitive the results would be to appropriate cyclical adjustments (see discussion below). Sakellaris and Wilson (2000) show that Nelson's approximation is unreasonable for US manufacturing firms. Instead they estimate a more general variant of the Solow–Nelson framework. Dividing (4) by Q_t we can write

$$\tilde{k}_{it+1} = \left(\frac{1-\delta}{1+\hat{Q}} \right) \tilde{k}_{it} + I_{it} \tag{11}$$

where $\tilde{k}_{it} = h_{it}/Q_t$. Let the production function for a plant be given by the same Cobb–Douglas function as before, then we can express it in logs as

$$\log y_{it} = \beta_0 + \beta_1 t + \beta_2 \log l_{it} + \beta_3 \log \tilde{k}_{it} + \varepsilon_{it}, \tag{12}$$

where $\varepsilon_{it} = \log A_{it} Q_t^{\alpha}$. In principle, one can then jointly estimate the nonlinear system of equations given by (11) and (12) and uncover an estimate of $\hat{Q}$, given an estimate of δ. Using this version of the model, Sakellaris and Wilson (2000) obtain a point estimate of the rate of ETC of about $\hat{Q} = 7.7\%$. One problem with the production–based estimation procedure is that unmeasured variation in the intensity with which plants utilize capital may lead to biases in production

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[7] Typically, one would also include other inputs such as materials or energy inputs as explanatory factors.

function estimation. To avoid this pitfall Sakellaris and Wilson proxy for capital utilization with energy use.[8] Specifically, they assume that capital utilization is a homogenous function of the ratio of energy use to the measured capital stock. When they do this, find that the estimated rate of embodied technological change rises substantially to $\hat{Q} = 17\%$ per annum.

2.2 Investment Specific Technological Change

Investment specific technological change (IST) refers to productivity improvements in the production of new efficiency units of investment goods, **relative to consumption goods**. It is **not** the same as improvements in the quality of capital services, although under some special circumstances IST and quality may turn out to grow at similar rates. To illustrate the concept of IST, let us consider a two–sector economy where one sector produces consumption goods, c_t, and the other produces efficiency units of investment goods, e_t. The consumption good is produced using labour effort, l_{ct}, and "efficiency units" of capital, h_{ct}, according to the following production function

$$c_t = A_t h_{ct}^{\alpha} l_{ct}^{1-\alpha}, \tag{13}$$

where A_t is a productivity parameter reflecting the level of technology used in the production of consumption goods. The efficiency units of the investment good, are produced by a representative firm using labour l_{et} and efficiency units of capital, h_{et}, according to

$$e_t = z_t A_t h_{et}^{\alpha} l_{et}^{1-\alpha}. \tag{14}$$

Here the term $z_t A_t$ reflects the technology used in the production of investment goods. Thus growth in z_t measures increments in the technical efficiency of the investment goods sector **relative** to the consumption goods sector. This is what Greenwood, Hercowitz and Krusell (1997) refer to as investment–specific technological change. Note that the capital share, α, is assumed to be the same in both sectors. This simplifies the analysis considerably by making aggregation simple, and does not appear to be significantly at odds with the facts for the US (see Hornstein and Krusell, 1996, for a discussion of the implications of allowing α to differ by sector). It is important to recognize that increases in the rate of IST increase the efficiency with which the efficiency units — the product of the quality and quantity of investment goods — can be produced. This distinction matters for investment incentives.

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[8] This approach was suggested by Jorgenson and Griliches (1967) and followed by Burnside et al. (1995) for industry–level estimation and Petropoulos (1999) for plant–level estimation. Fernald and Basu (1999) demonstrate the pitfalls arising from unmeasured factor utilization.

Aggregate efficiency units of capital stock are then divided between the two sectors:

$$h_{ct} + h_{et} = h_t, \tag{15}$$

where h_t evolves over time in the manner described in (4). If we assume further that factors are mobile across sectors and that there is perfect competition, then the capital–labour ratios in each sector are equal. Since the marginal product of each factor will be equalized across sectors, it follows that $p_{ct} = p_{et}z_t$. Thus, in principle, the rate of IST could be measured as the decline in the relative price of efficiency units of investment goods:

$$z_t = \frac{p_{ct}}{p_{et}}. \tag{16}$$

Using and extrapolating from Gordon's (1990) price data, Greenwood, Hercowitz and Krusell (1997) estimate that in the US, z_t grew at an average rate of 3.21% per year from 1954 to 1990. Their data also suggests that this growth rate accelerated after the mid–1970s.

Embodied technical change and IST are conceptually distinct: the former is an endogenous output from production and the latter is an exogenous input. However, under certain circumstances, the differences in their growth rates may be small. In particular, if the price of consumption goods, p_{ct}, grows at the same rate as the price of investment goods, p_{It}, then one could interpret this as implying that real investment is produced according to the same production technology as consumption and that all embodied technological change is exogenous IST. As the similarity between the estimate of $\hat{Q} = 3.44\%$ due to Hulten (1992) and that of $\hat{z} = 3.21\%$ due to Greenwood et al. (1997) suggests, between 1954 and 1990 the prices of consumption and investment goods grew at roughly equal rates on average.

3 The Contribution of ETC and IST to Growth

In the two sector economy described above the nominal value of aggregate output can be expressed as

$$V_t = p_{ct}c_t + p_{et}e_t = p_{ct}A_t h_{ct}^{\alpha} l_{ct}^{1-\alpha} + p_{et}z_t A_t h_{et}^{\alpha} l_{et}^{1-\alpha} \tag{17}$$

Since the $p_{ct} = p_{et}z_t$ and capital labour ratios are equal across sectors, this is equivalent to an aggregate production function representation given by

$$V_t = p_{ct}A_t h_t^{\alpha} l_t^{1-\alpha} \tag{18}$$

Now to determine real output growth, we must decompose nominal output growth into a component that is associated with real growth in GDP and a component associated with price inflation. It turns out that the way in which this is done has important consequences for the measurement of real GDP growth and the measurement of the contribution of IST to overall TFP growth. Two alternative frameworks exist, one draws from the earlier work of Domar (1963) and Jorgenson (1966) and the other from that of Solow (1957, 1960).

3.1 The Domar–Jorgenson Approach

3.1.1 Divisia Indices

To understand the Domar–Jorgenson approach, it is useful to review what has become the standard framework for generating indices of real output growth. There is no unique way to do this, but it has become the convention to use the approach first developed by Divisia (1925). The central issue is how to derive an index of real output from data on nominal expenditures on different goods. For example, suppose there are two goods in the economy: Apples, a, and Oranges, o. The total nominal value of the output of these goods is given by

$$v_t = p_t x_t = p_{at} a_t + p_{ot} o_t, \tag{19}$$

where p_a and p_o denote the prices of apples and oranges, respectively. But how do we decompose observable changes in the nominal value of output into unobserved changes in real output Q and price inflation? The Divisia framework generates an index of real output growth given by the "share–weighted" growth in the two outputs

$$\hat{x} = \gamma_t \hat{a} + (1 - \gamma_t)\hat{o}, \tag{20}$$

where

$$\gamma_t = \frac{p_{at} a_t}{p_t x_t} \tag{21}$$

is the share of expenditure on apples. The central idea behind this approach is that the share of expenditure on the good should reflect the relative value placed on it by society. Note that there is nothing to stop the shares changing over time.[9] Totally differentiating (19) yields

$$\hat{v} = \hat{p} + \hat{x} = \gamma_t (\hat{p}_a + \hat{a}) + (1 - \gamma_t)(\hat{p}_o + \hat{o}) \tag{22}$$

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[9] Because growth rates are computed in discrete time, the appropriate expenditure share is not clear. In practice, researchers have used the average share over the two relevant periods (the Tornqvist (1936) approximation). An alternative (and more precise) approach is to use Fisher (1965) "ideal chain–weighted indices". Until recently, the US national accounts used fixed weights that were adjusted every few years. However, in 1996 they started to compute real GDP using chain–weighted indices. Karl Whelan (2000) discusses the implication of these changes.

Subtracting (20) yields a growth in the price index (deflator) given by

$$\hat{p} = \gamma_t \hat{p}_a + (1 - \gamma_t)\hat{p}_o \tag{23}$$

It follows that we can then generate the growth in real output as

$$\hat{x} = \hat{v} - \hat{p} \tag{24}$$

Given some base year number for the index of real output, the growth rate can be used to compute a series in constant dollars.

Divisia indices have been used at the micro level to compute the aggregate "value added" in production and to compute the contribution of various sectors and industries to that value added (see for example, Jorgenson and Stiroh, 2000). Note that the notion of value added has been applied to industries producing both consumption and investment goods. Moreover a similar approach can be used on the input side — capital stock growth can be computed as the share–weighted growth in various types of capital and effective labour growth can be computed as the share–weighted growth in various types of labour (e.g. accounting for education and experience).[10] The issues involved in this procedure are discussed below.

3.1.2 Domar Aggregation

Domar (1963) and Jorgensen (1963) extend the use of Divisia indices to the study of aggregate GDP. The nice thing about this approach is that it is, in principle, consistent with industry level computations, especially those where consumption and investment goods are indistinguishable in output data.[11] The Domar–Jorgenson framework defines real aggregate output growth in terms of the value added in production. Real output growth is defined as the share–weighted average of the growth of real consumption and real investment (measured in efficiency units)

$$\hat{Y} = \gamma_t \hat{c} + (1 - \gamma_t)\hat{e} \tag{25}$$

where

$$\gamma_t = \frac{p_{ct} c_t}{p_t Y_t} \tag{26}$$

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[10] Note that such computations do not measure growth in the efficiency of each like unit of capital and labour. Such improvements will end up being bundled into the residual, unless independent estimates of them are incorporated into the analysis.

[11] In practise, however, a problem arises because intermediate inputs will be included at a disaggregate level, whereas they will "cancel out" in aggregate. The implications of this are discussed below.

is the share of consumption spending in overall expenditure given in (18). It follows that the appropriate price deflator for aggregate output grows at the rate

$$\hat{p} = \gamma_t \hat{p}_c + (1 - \gamma_t)\,\hat{p}_e \tag{27}$$

and real aggregate output growth can be measured as

$$\hat{Y} = \hat{V} - \hat{p}. \tag{28}$$

Jorgensen (1966) also assumes that aggregate value–added is produced according to an aggregate function of efficiency units of capital, labour effort and disembodied technological change. In particular the DJ framework implies the growth in value added equals

$$\hat{Y} = \hat{A}^* + \alpha_t \hat{B} + \alpha_t \hat{k} + (1 - \alpha_t)\hat{l} \tag{29}$$

where $\hat{A}^*$ is the aggregate rate of disembodied TFP growth, and

$$\alpha_t = \frac{p_{ht} h_t}{V_t},$$

denotes the share of capital expenditures in total output. This aggregate capital share can be computed as the residual after subtracting the labour share. Note that this approach imposes constant returns from the outset (see the discussion on imperfect competition below).

Jorgenson (2001) refers to $\hat{A}^*$ as total factor productivity growth and $\alpha_t \hat{B} + \alpha_t \hat{k}$ the contribution of capital input (which can then be broken down into capital quality and quantity). The reasoning is that in this framework, both the quality and quantity of capital were "produced" from inputs that could have been used to produce consumption.[12] For this framework, Hulten (1992) defines total factor productivity as the sum of disembodied and embodied technical change $\hat{A}^* + \alpha_t \hat{B}$. In doing so, he effectively assumes (like Solow, 1960) that all embodied technical change is the result of exogenous improvements in the production of investment goods (i.e. IST).

It is useful to disaggregate the analysis along the lines of the two sector framework discussed above. Totally differentiating (18) and using it to substitute for $\hat{V}$ in (28) yields

$$\hat{Y} = \hat{p}_{ct} + \hat{A} + \alpha_t \hat{B} + \alpha_t \hat{k} + (1 - \alpha_t)\hat{l} - \hat{p}. \tag{30}$$

Using (27) to substitute for $\hat{p}$ and noting that from (16) that $\hat{z} = \hat{p}_{ct} - \hat{p}_{et}$, we have

$$\hat{Y} = (1 - \gamma_t)\,\hat{z} + \hat{A} + \alpha_t \hat{B} + \alpha_t \hat{k} + (1 - \alpha_t)\hat{l}. \tag{31}$$

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[12] In effect, the possibility of investment specific technological change is ignored, because no allowance is made for the change in the relative price of consumption and efficiency units of investment goods.

It follows that in the D-J framework, the measured rate of disembodied technological change includes IST. In the context of the D-J framework, this makes sense: consumption and investment goods are treated symmetrically in generating real value–added, so aggregate disembodied technical change is just a weighted average of the disembodied technical change in each sector. Growth of "capital quality", $\hat{B}$, is treated entirely as a costly investment, just like "capital quantity", $\hat{k}$.

Hulten (1992) introduces the rate of average embodied efficiency, $\hat{B}$, that he estimates using Gordon's data, into the Domar–Jorgensen framework and uses (29) together with estimates of output growth, capital stock growth and labour force growth for the US manufacturing sector, to back out the implied rate of disembodied technical change, $\hat{A}^*$. Because he is restricted by Gordon's data, he assumes that embodied technical change has occurred only for producer–durable equipment. He finds that embodied technical change accounts for about 20% of overall (his definition of) TFP growth in the manufacturing sector between 1949 and 1983. That is

$$\frac{\alpha_e \hat{B}}{\hat{A}^* + \alpha_e \hat{B}} \simeq 0.20,$$

where $\alpha_e = 0.11$ is the cost share of equipment in production (rather than all capital). He also finds that the contribution rose from 16% before 1973 to 58% afterwards. Since TFP growth as a whole slowed from 1.88% per year before 1973 to 0.48% per year between 1974 and 1983, the increased importance of embodied technical change was mainly due to the precipitous decline in the growth of the residual (disembodied technical change).[13]

Note finally that we are often interested in labour productivity growth (i.e. the growth of GDP relative to hours of labour effort). Here that is given by

$$\hat{G} = \hat{Y} - \hat{l} = \hat{A}^* + \alpha_t \hat{B} + \alpha_t(\hat{k} - \hat{l}) \tag{32}$$

Based on Hulten's (1992) estimates, US labour productivity growth was approximately 3% on average over the period (3.8% before 1973, but falling to 1.77% afterwards). It follows that embodied technical change accounted for approximately 10% of labour productivity growth.

3.2 The "Generalized" Solow Approach

The Solow accounting framework differs from that of Domar and Jorgenson in that aggregate real output is defined in terms of consumption goods. This amounts to dividing (18) by the price

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[13] Care must be taken in interpreting this result because 1983 was close to the trough of a recession. The importance of cyclical adjustment is discussed below.

deflator for consumption goods instead of the Divisia index for output:

$$c_t + i_t = y_t = \frac{V_t}{p_{ct}} = A_t h_t^{\alpha} l_t^{1-\alpha} \tag{33}$$

where

$$i_t = \frac{p_{et} e_t}{p_{ct}} = \frac{e_t}{z_t} = \frac{Q_t I_t}{z_t} \tag{34}$$

denotes real investment in terms of consumption units.[14] In effect, the Solow framework defines real output as the consumption level that could be attained if all resources were allocated to the consumption sector, so that investment is deferred consumption.

It follows from (33) that growth in real output in consumption units can be expressed as

$$\hat{y} = \hat{A} + \alpha\hat{B} + \alpha\hat{k} + (1-\alpha)\hat{l}. \tag{35}$$

Solow (1960) and Hulten (1992) define TFP growth as the sum of the component of disembodied technical change that is common across sectors and the rate of embodied technical change, $\hat{A} + \alpha\hat{B}$. Clearly, real output growth in the D–J framework exceeds that in the Solow framework by an amount equal to $(1-\gamma_t)\hat{z}$.[15] If we think of GDP as a constraint on current activity, the Solow framework makes sense: greater IST today does not raise today's "potential" to consume, by raising current TFP, but only raises tomorrow's by yielding a greater effective capital stock through its affect on average embodied efficiency, $\hat{B}$.

Since measured TFP growth is lower than in the D–J framework ($\hat{A} < \hat{A}^*$), the Solow framework therefore attributes a greater fraction of it to the impact of embodied technical change, $\hat{B}$:

$$\frac{\alpha\hat{B}}{\hat{A} + \alpha\hat{B}} > \frac{\alpha\hat{B}}{\hat{A}^* + \alpha\hat{B}}. \tag{36}$$

If it were the case that the rate of IST contributes largely to quality improvements in new capital, so that $\hat{Q} \simeq \hat{z}$, then we could say that the Solow approach automatically attributes a greater fraction of TFP growth to IST than the D–J approach. Note that the two frameworks yield the same conclusions only if the rate of technical change in both sectors is the same. If one were to apply the Solow framework to the data provided by Hulten (1992) then, according to

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[14] The measure of real investment in consumption units, i_t, is equivalent to real investment in natural units, I_t, only if the rate of quality improvement equals the rate of IST, so that $p_{ct} = p_{It}$. Solow (1960) makes this assumption and this is one of the criticisms that Jorgenson (1966) makes of the framework. However, it is not necessary to impose this restriction, which is why I refer to this as the "generalized" Solow framework.

[15] This difference should be viewed as an adjustment for IST, not for quality as is often stated (e.g. Hulten, 1992).

my calculations, the contribution of embodied technical change to TFP growth would have been given by

$$\frac{\alpha_e \hat{B}}{\hat{A} + \alpha_e \hat{B}} \simeq 0.285$$

In the Solow framework, manufacturing labour productivity growth amounts to 2.55%, of which embodied technical change accounts for approximately 12%. Note that the contribution to labour productivity is not much different under the two frameworks. This is because the growth in capital, materials and services relative to labour swamps the impact of embodied technical change when computed at the industry level.

3.3 Allowing for Equilibrium Effects

As has been noted by many authors (e.g. Nelson 1964 and Hulten 1979), some fraction of observed growth in the capital stock reflects the endogenous response of capital accumulation to technological change. In principle, growth accounting procedures should adjust for this by attributing some of the output growth coming from capital formation to technological change. However, in practice, it is not clear how to do this. Suppose, as in the Solow (1956) growth model, investment is assumed to be a constant fraction of output. Then, if technical change is entirely labour–augmenting and the production function is well–behaved, the economy converges to a steady–state growth path along which output per worker and capital per worker grow at the rate of technical change.[16] This neoclassical growth model reaches very different conclusions to those of an accounting framework about the importance of technical change as a cause of economic growth. In the neoclassical growth model, capital formation explains **none** of the long–run steady state growth in output, because capital is itself endogenous and driven by technical change.[17] Because the accounting frameworks treat all capital as a wholly exogenous explanatory factor, it tends to overstate the role of capital and understate the role of innovation.[18]

In a similar way, the accounting frameworks treat the allocation of factors between different investment sectors as being exogenous. However, it is likely that the allocation of factors to the different sectors is in large part **caused by** the variations in the rates of technical change (and

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[16] Cass (1965) and Koopmans (1965) arrive at a similar long–run conclusion when the savings rate is determined optimally.

[17] Innovation causes output to increase, which increases investment, which thereby induces an expansion of the stock of capital.

[18] This matters for interpretation. If residual TFP growth "accounts" for 30% of labour productivity growth, it is not possible to say that a 1% decrease in TFP growth would reduce labour productivity growth by 0.3 %. This is because capital accumulation would decline in response.

hence the relative returns) in each sector. In particular, many argue that the rise in the share of output allocated to investment in IT over the last 25 years is in large part a response to the falling relative price. That is, to measure the true contribution of IST one must take account of this induced reallocation towards the durable equipment producing sector. Greenwood, Hercowitz and Krusell (1997) allow for this effect in a general equilibrium neoclassical growth model in which there is IST and the rate of investment is determined optimally via the households savings decision.

Greenwood et al. (1997) calibrate their model to match various stylized facts for the aggregate US economy including the rate of IST based on Gordon's (1990) data and the investment share of the various sectors of the economy over the period 1954–1990. They then back out the implied rate of residual technical change and compute the relative contribution of it and IST to overall labour productivity growth. In doing so, they take account of the impact that IST has on efficiency units of investment across different sectors.

Greenwood et al. (1997) estimate that aggregate labour productivity grew at 1.24% over the period,[19] and that the contribution of IST to this was approximately 58%. That is

$$\frac{\alpha_e \left(\hat{h} - \hat{h}_{z=0}\right)}{\hat{A} + \alpha(\hat{h} - \hat{l})} \simeq 0.58,$$

where $\hat{h}_{z=0}$ denotes the implied rate of capital growth when IST is set equal to zero, ceteris paribus. Note also that the output share of equipment, $\alpha_e = 0.17$, is higher and the growth in labour productivity lower than in Hulten (1992) because "output" here is defined as aggregate value added, not gross output in manufacturing. In general, it is difficult to compare these results with those of Hulten on embodied technological change. However, if we were to assume that with no IST there would be no improvement in quality, then

$$\hat{h} - \hat{h}_{\hat{z}=0} \simeq \hat{B} + \hat{k} - \hat{k}_{\hat{z}=0}.$$

Assuming that $\hat{B} = 0.03$, the contribution of the induced effect of IST on the quality of capital to labour productivity growth would be 38% with the remaining 20% coming from the induced effect of IST on the quantity of capital in natural units.[20] Reducing the share of equipment to 0.11 (as in Hulten) would imply 25 % and 13% respectively. Note that because investment (in both quality

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[19] The difference in unadjusted labour productivity growth relative to Hulten (1992) reflects the fact Greenwood et al. (1997) use value added for the entire economy, not gross output for the manufacturing sector.

[20] Hercowitz (1998) reaches a similar conclusion.

and quantity) is assumed to be wholly endogenous, it is not possible to provide a meaningful measure of the contribution of IST to TFP growth, as in the pure accounting frameworks.

3.4 Discussion

Clearly, the importance of IST depends on the accounting framework that we use. But which framework should be used ? Which is correct ? In the Domar–Jorgenson framework a higher rate of IST today raises current GDP growth because it raises value added directly. The fact that an increase in IST has such a *disembodied* impact on current output growth in this case, reflects the fact that the measure of real value–added treats both investment goods and consumptions goods as the end in themselves. But the value to households of investment goods derives from the additional consumption that they will generate in the future, and that depends on the *embodied* impact on the future capital stock. In this sense, the Solow framework seems to provide a more meaningful measure of GDP and, hence, labour productivity growth.

Jorgenson and Stiroh (1999) and Jorgenson (2001) have also criticized the conclusions of Greenwood et al. (1997) on the grounds that by basing their analysis on the Solow framework, they implicitly assume that investment and consumption goods are perfect substitutes. However, this criticism only applies if we interpret IST as being the *same as* embodied technical change. If we assume (as Greenwood et al. do) that investment (both in quality and quantity) is endogenously driven, then it is correct to interpret some fraction of this investment, and hence output growth, as being *caused by* IST.[21] In a general equilibrium context, it makes no sense to think of embodied technical change as "causing" any productivity growth. To see this, recall that investors make no distinction between I and Q. Investors simply choose factor allocations to achieve (amongst other things) the optimal level of capital services, e^*. Hence, an increase in the rate of growth in Q would not *cause* increased productivity growth.

Note, however, that Greenwood et al. (1997) make some problematic assumptions in computing the effective capital stock. The Domar–Jorgenson approach requires a measure of the growth in the aggregate real capital stock both in natural and efficiency units. For each type of capital these are computed according to (4) and (6) above, and the growth in the aggregate capital stock is computed as the share–weighted average of the growth of the various capital stocks. Note that

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[21] It turns out that in the US, over the last few decades the ratio of theprice of consumption and investment goods has been pretty constant, which is consistent with the view that IST has largely led and embodied technical change (see Sakellaris and Wilson, 2000).

the weights require a computation of the price of each type of capital in service (Jorgenson and Griliches (1964) refer to these prices as "service prices"). To obtain these prices, requires the computation of the user–cost of capital along the lines of Jorgenson and Hall (1963). In their pioneering work, Griliches and Jorgenson (1964) found that allowing for this adjustment in the shares of different types of capital greatly increased the proportion of labour productivity growth that could be attributed to capital formation (from 52.4 % to 82.7 % over the period 1945–65).

In principle the same aggregation approach could be used in the generalized Solow framework. However, Greenwood et al. (1997) only distinguish between two types of capital (equipment and structures) and implicitly assume that the expenditure shares on each in the total value in of the capital stock have remained constant over time. Fixing the shares is necessary to solve for the optimal path of the economy, but appears to be inconsistent with the fact that the share of durable equipment in the value of the capital stock appears to have significantly grown over time.[22] Thus, they miss the (potentially large) increase in the effective capital stock due to this effect, which is a costly re–allocation (the relative prices reflect the relative marginal products of the capital) and so should be viewed as part of capital formation.

Another criticism of the Greenwood et al. (1997) approach is that it assumes that all investment is an endogenous response and that households behave in a fully rational fashion to maximize a CES utility function. According to most empirical work, actual savings behaviour does not conform that well with the optimal savings behaviour implied by this model, so it is not clear how to interpret the predictions of their analysis. However, it should be recognized that the conventional accounting approach in which capital formation is treated exogenously is not model–independent either.[23] In general, it would be useful to be able to distinguish between exogenous and induced capital formation. However, it is not clear what is the correct approach to doing this (see also Hulten, 1996).

It is worth noting that one could consider the impacts of IST in a Solow accounting framework, without allowing for the fact that investment is partly endogenous. In such a framework, some fraction of the accumulation of the capital input ($\hat{B} + \hat{k}$) would be directly due to the effects of IST and some would be due to costly (in terms of consumption) capital formation. According to this perspective, the fraction of capital formation that is due to IST would lie between zero, as

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[22] After accounting for the price decline.

[23] It is often stated that the conventional approach is model–independent because it does not impose a savings choice on the data. However, this is not the case: capital formation is assumed to be exogenous.

assumed by Jorgenson (2001), and one, as assumed by Greenwood et al. (1997). By taking this accounting approach, one could also relax the assumption that the share of equipment in capital is fixed.

4 Related Measurement Issues

4.1 Cyclical Adjustment

In my discussion above, I treated the economy as if it were always in a full employment equilibrium. In practice, the aggregate production function should be thought of as representing the **potential output** that could be produced if all factors (labour and capital) were fully utilized. This was well understood in the early analyses of Solow (1957, 1960) and Nelson (1964), who recognized that measured capital stocks must be corrected for the degree of utilization, otherwise the implied disembodied TFP would be biased downwards during periods of economic slack.[24] However, their approach to correcting for variation in utilization was fairly crude. They used the so–called Okun adjustment, which essentially adjusted for the deviation of the unemployment rate from its trend rate. The same adjustment was applied to capital, thereby implicitly imposing some kind of putty–clay technology in which the production function is Leontief in the short–run.

In their pioneering study, Jorgenson and Griliches (1967) attempted to adjust for the cyclical utilization of capital and labour separately. They assumed that the relative utilization of capital is the same for all capital goods and estimate it from the relative utilization of electric power in manufacturing. Unfortunately, their adjustment only allowed for the trend in the relative utilization of capital and not for short–term cyclical variations. More recently however, other researchers have used measures of energy usage and other intermediate inputs to adjust for short term cyclical utilization of factors in related contexts (see, for example, Burnside, Eichenbaum and Rebelo, 1995, Basu, 1996, Petropolous 1999, and Sakellaris and Wilson, 2000, Baldwin, Gaudreault and Harchaoui, 2001). Cyclical adjustment has proved especially important in determining whether labour productivity growth increases during the late 1990s reflect a purely cyclical upturn or underlying structural change (see Section 5).

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[24] Interestingly, this fact was not allowed for by RBC researchers (with a few exceptions) until recently. For example, King and Rebelo (1999) note that once one builds in endogenous capacity utilization, measured TFP movements are much smaller and rarely negative. However, in the presence of endogenous capacity utilization the impact of productivity shocks on other aggregate variables is greatly magnified.

4.2 Quality Improvements in Consumer Goods

So far, we have assumed that only investment goods are subject to quality improvements. However, it is also the case that consumer goods should be measured in something akin to efficiency units, in which case the conventional consumer price index does not reflect quality improvements. Let Q_c represent the quality of consumer goods. Then the relevant measure of consumer goods is given by

$$d_t = Q_{ct} c_t \tag{37}$$

and quality can be measured as

$$Q_{ct} = \frac{p_{ct}}{p_{dt}} \tag{38}$$

Although some adjustment in quality has been factored into the US CPI, the Advisory Commission to Study the Consumer Price Index (1996) estimates that Q_{ct} has grown at an average of 0.6% per year faster than official price statistic indicate. However, the commission cites only a handful of studies in arriving at this estimate. More recently, Bils and Klenow (2001) introduce an instrumental variables approach and use it to estimate the rate of unmeasured quality growth for 66 durable consumer goods that constitute over 80% of US spending on consumer durables and 12% of CPI. They estimate that between 1980 and 1996, the quality of these goods has grown by 3.7% per year, and that 2.2% per year is not captured by official statistics. Such quality improvements imply that GDP has grown at a higher rate than conventional measures imply, but the size of the increase again depends on the accounting framework.[25]

In the Domar–Jorgenson framework, real output growth would now be given by

$$\hat{Y} = \gamma_t \hat{d} + (1 - \gamma_t)\hat{e}, \tag{39}$$

where

$$\gamma_t = \frac{p_{dt} d_t}{p_{dt} d_t + p_{et} e_t}. \tag{40}$$

Suppose that in the two sector economy described above, (13) is replaced by a production function for efficiency units of consumer goods given by

$$d_t = A_{dt} h_{dt}^{\alpha} l_{dt}^{1-\alpha}, \tag{41}$$

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[25] Because, Bils and Klenow's (2001) estimate is based on durables it does not measure the per–period improvement in the quality of the services of those durables that is actually consumed.

and the production function for efficiency units of investment goods would be expressed as

$$e_t = z_t^* A_{dt} h_{et}^{\alpha} l_{et}^{1-\alpha}, \tag{42}$$

where $z_t^* A_{dt} = z_t A_t$. Here the rate of IST would be measured by the decline in the price of efficiency units of investment goods relative to the efficiency units of consumption goods:

$$z_t^* = \frac{p_{dt}}{p_{et}} \tag{43}$$

Then, under Domar aggregation, output growth would be expressed as

$$\hat{Y}^* = (1-\gamma_t)\hat{z}^* + \hat{A}_d + \alpha\hat{B} + \alpha\hat{k} + (1-\alpha)\hat{l}. \tag{44}$$

This exceeds the previous measure by $\gamma_t(\hat{z} - \hat{z}^*) = \gamma_t(\hat{p}_c - \hat{p}_d) = \gamma_t\hat{Q}_c$.

In contrast Solow aggregation would express GDP growth in terms of efficiency units of consumption as

$$\hat{y} = \hat{A}_c + \alpha\hat{B} + \alpha\hat{k} + (1-\alpha)\hat{l} \tag{45}$$

This exceeds the previous measure by $\hat{z} - \hat{z}^* = \hat{p}_c - \hat{p}_d = \hat{Q}_c$. Thus, it can be seen that adjusting output growth for quality improvements in consumer goods increases the rate computed in the Solow framework by more than it increases it in the D-J framework. As before, output growth under the D–J framework exceeds that under the Solow framework by the share–weighted rate of IST $(1-\gamma_t)\hat{z}^*$, where the rate of IST is now given by (43) instead of (16). Note that the greater the rate of quality improvement in consumer goods, the lower will be the implied rate and contribution of IST. If, for example, we assume that unmeasured quality of the services provided by consumer goods is 2.2%, then the implied rate of IST would only be 1% per year. Note, however, that Greenwood et al. (1997) use only non–durable consumption in their analysis, so this does not apply.

4.3 Technological Obsolescence

In calculating the effective capital stock, h_t, above, we effectively assumed that firms will never choose to retire equipment that retains productive capacity.[26] Rather, we followed the assumption of Solow's vintage capital model that the optimal strategy is simply to let the flow of income from a computer, say, gradually erode over time. In general, this is not the case: computers and other

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[26] This is also the assumption implicit in the calculations of the BEA and Statistics Canada.

IT equipment are retired while they still retain productive capacity. One reason for this is the large costs that must be incurred for technical support and maintenance: once the marginal product of the equipment falls below these costs it becomes optimal to retire it. It turns out that ignoring this **technological obsolescence** leads official statistics to overestimate the rate of depreciation and hence, to underestimate the stock of IT related capital in the economy.

To understand the problem note that, following the work of Oliner (1989), the effective physical depreciation rate in the NIPAs is inferred from a hedonic price regression which has the following form:

$$\log p_a(t) = \beta t + \theta \log Q_a(t) + \delta a, \tag{46}$$

where $p_a(t)$ is the time t price of a machine of age a, $Q_a(t)$ describes quality of the machine (described by a vector of characteristics embodied in the machine), and δ_e measures the marginal impact of the age of the capital on the price (adjusting for quality improvements). In the NIPA's official statistics, δ is interpreted as the physical depreciation rate. However, if there is technological obsolescence, the price of the capital will also fall with age as the retirement date approaches. It follows that the marginal impact of age on the price is not just due to physical depreciation: so interpreting the parameter estimate this way, will lead δ to be an overestimate of the actual physical depreciation rate, δ^*. With technological obsolescence, so that capital is retired at some age T, the effective capital stock is given by

$$h_{t+1} = (1 - \delta^*)h_t + e_t - \frac{e_{t-T}}{(1 + \delta^*)^T} \tag{47}$$

Although the estimated capital stock is reduced by the direct effect of retirement, if T is sufficiently large, the impact of correcting the depreciation rate downwards may substantially outweigh this effect, causing the effective capital stock to increase.

Whelan (2000) develops a method for estimating the productive equipment capital stock with endogenous technological obsolescence. He finds that the corrected effective capital stocks of PCs (the largest category) was approximately 44% larger than that estimated by the NIPA. Although, this error does not effect the growth rate of the IT capital stock much, it does affect the estimated share of IT equipment in the overall capital stock, and hence the contribution of its growth to overall labour productivity growth. Using a variant of the Domar–Jorgenson framework, he estimates that between 1974 and 1995, 43% of labour productivity growth in the US business sector came from computer related effects (26% from capital accumulation and 17% from TFP growth), and that this accelerated to 57% between 1996 and 1998 (35% and 22%).

4.4 Aggregate versus Industry Level Accounting

My discussion above is largely carried out at the aggregate level. However, in the case of Hulten (1992) for example, the actual quantitative analysis was based on the input and output data of the US manufacturing sector. More generally, it should in principle be possible to aggregate up from the accounts of individual industries so as to derive a consistent set of accounts. In practice, however, this is complicated by the existence of intermediate goods — some of the inputs of any industry are themselves outputs of other industries. While at the aggregate expenditure level, these intermediates cancel out, so that aggregate value added equals the aggregate payments to factors, at the industry level some of the output is not final and some of the inputs are not primary factors. This leads to the following accounting identity for industry i:

$$p_i y_i + p_i \sum_j M_{i,j} = w_i L_i + r_i K_i + \sum_j p_j M_{j,i} \tag{48}$$

The standard approach to dealing with this (used by the BLS and Statistics Canada) is to focus on the right hand side of this expression and define industry output as the "real" part of $w_i L_i + r_i K_i$. Industry value added sums to total value added (GDP), and the relationship between the two is not affected by intermediate goods. There are however two problems with this approach. First, there is nothing in the real world that resembles real value added, so at the industry level it is not clear how to interpret these numbers. Second, this approach only works when innovation enhances the productivity of capital and labour, but not intermediate inputs (i.e. the industry level production function has the form $Q_i = F[M_i, A_i G(K_i, L_i)]$. Some researchers (e.g. Jorgenson and Stiroh, 2000) use gross output when discussing disaggregate industry data, while others (e.g. Basu, Fernald and Shapiro, 2000) use real value added. The latter assume that gross output can be expressed as $\hat{Q}_i = \zeta \hat{M}_i + (1-\zeta)\hat{V}_i$, where ζ_t denotes the share of intermediates in total output, then define value added as

$$\hat{V}_i = \frac{\hat{Q}_i - \zeta_t \hat{M}_i}{(1-\zeta_t)}. \tag{49}$$

5 Evaluating the Evidence of Recent Structural Change

5.1 Decomposing Cycle and Trend in Productivity Growth

By structural change growth economists typically mean a significant break in the trend rate of some component of labour productivity growth. Such structural changes are typically rather difficult to identify close to the time at which they occur, mainly because it is difficult to distinguish long–term changes from cyclical effects.[27] Most growth economists seem to agree that some kind of structural break in labour productivity occurred around 1973, although some believe that the productivity slowdown began earlier. Recently, many have argued that the high growth in US labour productivity during the late 1990s represented another structural change in productivity growth associated with new economy technologies. However, in order to determine whether such a change has indeed occurred it is necessary to decompose the movements into structural and cyclical components.

In his well–known critique of the New Economy view, Gordon (2000) also uses a fairly crude approach to decompose US productivity growth during the 1990s into its cyclical and trend components. He uses quarterly labour–productivity data for the private business and manufacturing sectors to "back out" a series on labour productivity outside of manufacturing durables, which he then attempts to decompose econometrically into trend versus cycle.[28] He finds that of the actual 2.82% growth in output per hour between 1995 and 1999, 0.54 is attributable to a cyclical effect and the remaining 2.28% to trend growth. The latter is 0.81% faster than the 1972–95 trend. He finds that the majority of this acceleration (0.62 percentage points) can be directly attributed to the IT–related sectors: 0.33 percentage points was due to capital deepening and the remainder (0.29 percentage points) to TFP growth in these sectors.[29]

Roberts (2001) takes a somewhat more sophisticated approach by using a time–varying parameter technique to isolate trend from cyclical movements in productivity and to estimate the trend rate of productivity growth. He accounts for cyclical influences using a trend–and–cycle model based on those of Watson (1986) and Clark (1987), extended by including data on hours as

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[27] As discussed below, this problem may have important consequences for wage–setting and, hence, for monetary policy.

[28] In his specification, the change in the growth of hours relative to trend $(l - l^*)$ is explained by changes in the growth of output relative to trend $(Y - Y^*)$. The trend in hours is set at rate consistent with a NAIRU of 5%, and the trend in output growth is chosen to fit according to a grid–search method.

[29] The remaining 0.19 percentage points are accounted for by improvements in labour quality (0.05) and price mis–measurement (0.14).

well as output. He estimates that trend labour productivity growth accelerated from around 1.5% between 1972–1995 to 2.5% from 1995–2000. Roberts (2001) goes on to consider an extension of his model that allows for a direct effect of the capital stock on labour productivity. He finds that trend TFP growth accelerated from 3/4% in the early 1990s to 1% in the late 1990s. In contrast to Gordon he finds that very little of the acceleration in labour productivity growth was due to cyclical factors (about 0.1 %).

Basu, Fernald and Shapiro (2000) model utilization as an optimal choice of the firm in the face of quadratic capital adjustment costs. Because it is costly to adjust the capital stock, a firm may optimally leave some capital idle in the short–run rather than reduce it and then increase it when demand increases. Once solved, their model yields an indirect production function which they calibrate and use with observable inputs. Basu, Fernald and Shapiro (2000) also point out that under conditions of short–run imperfect competition, business cycles could also result in reallocation effects across industries which would lead to changes in aggregate labour productivity. Their results imply that (1) while cyclical utilization accounts for some of the behaviour of measured productivity during the early part of the 1990s expansion, it does not explain the acceleration in productivity at the end of the decade, (2) adjustment costs from the onset of the boom initially obscured the acceleration in technology, (3) there was substantial acceleration in the pace of technological change in the latter half of the 1990s, (4) durable manufacturing experienced the fastest rate of technology growth and the largest acceleration,[30] and (5) although non–durable manufacturing experienced very slow growth, non–manufacturing shows a marked acceleration in adjusted TFP growth relative to its recent performance.[31]

5.2 The Role of IST

All of the analyses that have attempted to cyclically decompose US productivity growth in the 1990s, have been based on the Domar–Jorgenson framework. This implies that they implicitly assume that much of the growth in labour productivity during the late 1990s was associated with costly capital formation. However, in the Solow framework, some of this growth in capital may have arisen from a reduction in the opportunity cost of producing investment goods (a form of TFP growth).

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[30] In the last half of the 1990s, it increased over 6% per year.

[31] Baldwin et al. (2001) undertake a related decomposition for Canada with similar results. However, their data only goes up to 1995.

— To Be Completed —

5.3 Implications for Monetary Policy

Over long periods, labor productivity and real product wages (hourly compensation deflated by the price of output) move in tandem, because businesses can afford to give real wage increases that are justified by productivity gains, and competition forces them to do so. Eventually, a change in the rate of productivity growth tends to be matched by an equal change in the growth of both actual and anticipated real wages. Breaks in trend productivity growth, however, are difficult to recognize, and therefore wage and price inflation adjust only gradually to any change. The productivity slowdown after 1973 at that time elevated the NAIRU and contributed — along with demographics, oil price increases, and strong demand — to rising inflation in the late 1970s. During that period, nominal hourly compensation increased at a rate that would have been consistent with stable inflation if productivity had still been growing at its pre-1973 trend. Instead, because trend productivity growth had fallen, the higher compensation resulted in rising inflation of unit labor costs and prices. Making matters worse, many wage setters adjusted to the higher rate of inflation, creating a wage-price spiral.

Some economists have argued that the apparent acceleration in productivity after 1995 may have initiated a similar process, but in reverse, allowing the unemployment rate to fall lower, with less consequence for inflation, than would have been possible otherwise. The rate of growth of nominal hourly compensation has increased during recent years, but these nominal increases have not resulted in rising price inflation. Businesses have been able to grant these larger pay increases without raising price inflation, partly because increases in unit labor costs have remained stable as rising productivity growth offset the rising compensation gains. The new, higher trend growth rate of productivity since 1995 could have temporarily lowered the NAIRU, because it can take many years for firms and workers to recognize this favorable development and incorporate it into their wage-setting process. In the meantime, the productivity surprise can stabilize inflation of unit labor costs and prices even at unemployment rates below the previous NAIRU. The effect of the increase in productivity growth on unemployment probably will not last indefinitely. If trend productivity growth really has increased, it will cease to be "unexpected," the real wage norm will eventually rise to that same level, and the short-term NAIRU will gravitate back to its long-term level.

6 Concluding Remarks

In this survey I have argued that the validity of the hypothesis that we are entering a "new economy" era in which underlying total factor productivity growth will be significantly higher than in the previous two or three decades, depends crucially on the growth accounting framework that is used. In the presence of rapid investment–specific technological change, the Domar–Jorgenson and "generalized" Solow accounting frameworks can yield widely different interpretations of the same observed data. The crucial issue relates to how much of the growth in the effective capital stock has been the result of costly deferment of consumption or exogenous reductions in opportunity cost of investment in terms of consumption.

According to Jorgenson (2001), Jorgenson and Stiroh (2000), Gordon (2000) etc. the small impact on TFP during the 1980s and early 1990s noted by Solow is due to the fact that (1) the relevant sectors of the economy were small and (2) most of the effect came through the observed improvements in the quality of capital which reflects substitution towards more productive forms of capital. In other words, producers of durable equipment successfully reaped the returns to their investments and there was very little "shift" in the production possibilities frontier. Although this view admits that there was a high rate of technological change in these equipment producing sectors, it effectively assumes that the opportunity cost of capital formation in terms of consumption did not change.

According to the alternative view espoused by Greenwood et al. (1997), Hercowitz (1998) and Harbeger (1998), much of the growth in the quality and quantity of capital during the 1980s came from exogenous IST which effectively reduced the opportunity cost (in terms of consumption) of investment in durable equipment. According to this view, only some of the increase in efficiency units of capital was due to costly capital formation that required reduced consumption, the rest was due to exogenous (investment–specific) technical change. The tricky issue with this alternative view is to determine how much of the increase in efficiency units was a result of IST and how much was due to costly capital formation. The findings of Greenwood et al. (1997) suggest that the majority of it came from IST.

References

[1] Advisory Commission to Study the Consumer Price Index (1996), *Towards a More Accurate Measure of the Cost of Living*, Final Report to the Senate Finance Committee, Washington D.C., December 4.

[2] Bahk, Byon–Hyong and Michael Gort (1993), "Decomposing Learning by Doing New Plants", *Journal of Political Economy*, vol. 101 (4), pp. 561–583.

[3] Baily, Martin N. and Robert J. Gordon, (1988), "Measurement Issues, the Productivity Slowdown and the Explosion of Computer Power", *Brookings Papers on Economic Activity*, (2), pp. 347–420.

[4] Baldwin, John, Valerie Gaudreault and Tarek, M. Harchaoui, "Productivity Growth in the Canadian Manufacturing Sector: A Departure from the Standard Framework," chapter 8, *Productivity Growth in Canada*, Statistics Canada Catalogue Number 15-204-XPE.

[5] Basu, Susanto, John G. Fernald and Matthew D. Shapiro (2000), "Productivity Growth in the 1990s: Technology, Utilization or Adjustment?" mimeo, University of Michigan, November.

[6] Berndt, Ernst R., Zvi Griliches and Neal R. Rappaport, "Econometric Estimates of Price Indexes for Personal Computers in the 1990s," *Journal of Econometrics*, vol. 68, pp. 243–268.

[7] Bils, M. and P. Klenow (2001), "Quantifying Quality Growth," *American Economic Review*, vol. 91 (4), pp. 1006–1030.

[8] Burnside, Craig, Martin Eichenbaum and Sergio Rebelo (1995), "Capital Utilization and Returns to Scale," in Julio J. Rotemberg and Ben S. Bernanke (eds.), *NBER Macroeconomics Annual 1995.* Cambridge, MA: MIT Press.

[9] Campbell, Jeffrey R. (2000), "Entry, Exit, Embodied Technology and Business Cycles," *Review of Economic Dynamics*

[10] Cole, Rosanne, Y.C. Chen, J.A Barquin-Stolleman, E. Dullberger, N. Helvacian and J.H. Hodge (1986), "Quality–Adjusted Price Indexes for Computer Processors and Selected Peripheral Equipment," *Survey of Current Business*, vol 66, pp. 41–50.

[11] Denison, Edward F. (1964), "The Unimportance of the Embodiment Question," *American Economic Review*, vol. 54, pp. 90–94.

[12] Denison, Edward F., (1989), *Estimes of Productivity Change by Industry*, Washington, D.C.: The Brookings Institution.

[13] Divisia, F. (1925), "L'Indice Monétaire et la Théorie de la Monnaie", *Revue d'Economique Politique*, vol. 34, (4,5,6), pp. 842–61, 980–1008, 1121–51.

[14] Domar, Evsey D. (1963), "Total Factor Productivity and the Quality of Capital," *Journal of Political Economy*, vol. 71, pp. 586–8.

[15] Fernald, John and Susanto Basu, (1999), "Why is Productivity Procyclical? Why do we Care?" Board of Governers of the Federal Reserve System, IFDP No. 638.

[16] Fisher, Franklin M. (1965), "Embodied Technical Change and the Existence of an Aggregate Capital Stock," *Review of Economic Studies*, vol. 32, pp. 263–288.

[17] Gordon, Robert J. (1990), *The Measurement of Durable Goods Prices*, Chicago: University of Chicago Press.

[18] Gordon, Robert J. (1996), "Can Technology Improvements Cause Productivity Slowdowns ? Comment," in Julio J. Rotemberg and Ben S. Bernanke (eds.) *NBER Macroeconomics Annual 1996*. Cambridge, MA: MIT Press.

[19] Gordon, Robert J. (2000), "Does the "New Economy" Measure Up to the Great Inventions of the Past?" NBER Working Paper 7833.

[20] Gort, M.J., J. Greenwood and P. Rupert (1999), "Measuring the rate of Technological Progress in Structures," *Review of Economic Dynamics.*

[21] Gort, M.J. and R. Wall (1998), "Obsolescence, Input Augmentation and Growth Accounting," *European Economic Review*, vol. 42, pp. 1653–65.

[22] Greenwood, J., Z. Hercowitz and P. Krusell (1997), "Long Run Implications of Investment–Specific Technological Change," *American Economic Review* vol. 87 (3), pp. 342–362.

[23] Greenwood, J., Z. Hercowitz and P. Krusell (2000), "The Role of Investment–Specific Technological Change in the Business Cycle," *European Economic Review*, vol. 44(1), pp. 91–115.

[24] Greenwood, J and M. Yorokoglu (1997), "1974" Carnegie–Rochester Conference Series on Public Policy, vol. 46, pp. 499-95.

[25] Gregory, R.G. and Dennis W. James (1973), "Do New Factories Embody Best Practise Technology?" Economic Journal, vol. 83, pp. 1133–55.

[26] Griliches, Zvi (1961), "Hedonic Price Indexes for Automobiles: An Econometric Analysis of Quality Change," in The Price Statistics of the Federal Government: Review Appraisal and Recommendations, New York: NBER pp. 137–96.

[27] Griliches, Zvi, "The Discovery of the Residual: A Historical Note," Journal of Economic Literature, vo. 34, pp. 1324–1330.

[28] Hall, Robert E. (1968), "Technical Change and Capital from the Point of View of the Dual," Review of Economic Studies, vol. 35, pp. 34-46.

[29] Hercowitz, Zvi (1998), "The 'embodiment' hypothesis," Journal of Monetary Economics, vol. 41 (1), pp. 217–24.

[30] Hornstein, Andreas and Per Krusell (1996), "Can technology improvements cause productivity slowdowns ?" in Julio J. Rotemberg and Ben S. Bernanke (eds.) NBER Macroeconomics Annual 1996. Cambridge, MA: MIT Press.

[31] Hulten, C.R. (1979), "On the Importance of Productivity Change," American Economic Review, vol. 69 (1), pp.126–136.

[32] Hulten, Charles R. (1992) "Growth Accounting when Technological Change is Embodied in Capital," American Economic Review vol. 82 (4), pp. 964–980.

[33] Hulten, Charles R. and Frank C. Wykoff, "The Measurement of Economic Depreciation," in Charles R. Hulten, ed. Depreciation, Inflation and the Taxation of Income from Capital, Washington: The Urban Institute Press.

[34] Johansen, Leif, "Substitution versus Fixed Production Coefficients in the Theory of Economic Growth: A Synthesis," Econometrica, vol. 27, pp. 157–76.

[35] Jorgenson, Dale W. (1966), "The Embodiment Hypothesis," Journal of Political Economy, vol. 74, pp. 1–17.

[36] Jorgenson, Dale W. and Zvi Griliches (1967), "The Explanation of Productivity Change," Review of Economic Studies, vol. 34, pp. 249–83.

[37] Jorgenson, Dale W. and Kevin J. Stiroh (2000), "Raising the Speed Limit: U.S. Economic Growth in the Information Age," **Brookings Papers on Economic Activity**, vol. 31 (1).

[38] Oliner, Stephen D. (1989), "Constant–Quality Price Change, Depreciation and Retirement of Mainframe Computers," in **Price Measurements and their Uses**, ed. Allan Young, Murray Fuss and Marilyn Manser, Chicago: University of Chicago Press.

[39] Oliner, Stephen D. and Daniel E. Sichel (2000), "The Resurgence of Growth in the Late 1990s: Is Information Technology the Story?", **Journal of Economic Perspectives**, vol. 14, pp. 3–22.

[40] Petropoulos, Wendy (1999), "Industry Productivity Dynamics and Unmeasured Capacity Utilization," University of Michigan.

[41] Roberts, John M. (2001), "Estimates of the Productivity Trend Using Time–Varying Parameter Techniques", **Contributions to Macroeconomics (B.E. Journals in Macroeconomics)**, vol. 1 (1), Article 3.

[42] Sakellaris, Plutarchos and Daniel J. Wilson, "The Production–Side Approach to Estimating Embodied Technological Change," mimeo, University of Maryland.

[43] Salter, W.E.G., **Productivity and Technical Change**, Cambridge: Cambridge University Press, 1960.

[44] Solow, Robert M. (1957), "Technical Change and the Aggregate Production Function," **Review of Economics and Statistics**, vol. 39, pp. 312–20.

[45] Solow, Robert M. (1960), "Investment and Technical Progress," in K. Arrow, S. Karlin and P. Suppes, eds., **Mathematical Methods in the Social Sciences, 1959**, Stanford, CA: Stanford University Press, pp. 89–104.

[46] Solow, Robert M. (1987), Book Review, **New York Times**, July 12, p. 36.

[47] Statistics Canada (2001), **Productivity Growth in Canada**, Catalogue No. 15–204–XPE.

[48] Stiroh, Kevin J. (1998) "Computers, Productivity and Input Substitution," **Economic Inquiry**, vol. 36 (2), pp. 175-91.

[49] Tornqvist, L. (1936), "The Bank of Finland's Consumption Price Index," **Bank of Finland Monthly Bulletin**, vol. 10, pp. 1–8.

[50] Triplett, Jack E. (1983), "Concepts of Quality in Input and Output Price Measures: A Resolution of the User Value–Resource Cost Debate," in Murray F. Foss, ed., **The U.S. National Income and Product Accounts: Selected Topics**, Studies in Income and Wealth, vol. 47, Chicago: University of Chicago Press for the NBER, pp. 296–311.

[51] Triplett, Jack E. (1999), "The Solow Computer Paradox: What do Computers do to Productivity?", **Canadian Journal of Economics**, vol. 32 (2), pp. 309–34.

[52] Whelan, Karl (2000a), "Computers, Obsolescence and Productivity," Working paper, Board of Governors of the Federal Reserve.

[53] Whelan, Karl (2000b), "A Guide to the Use of Chain Aggregated NIPA Data," Working paper, Board of Governors of the Federal Reserve.

[54] Young, Alwyn, "The Tyranny of Numbers: Confronting the Statistical Realities of the East Asian Experience," **The Quarterly Journal of Economics**, pp. 641–680.