Intangible Assets and Growth Accounting:
Evidence from Computer Investments

Preliminary and Incomplete –

Comments Welcome.

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This paper revises growth accounting methodology to take into account the value of intangible assets, particularly those associated with the computerization of many firms in recent decades. We propose a modification of the production function, adopted from the q theory of investment, that treats the adjustment costs and costs associated with the creation of intangible complementary assets as investments instead of current expenditures. We present evidence that the computer-related portion of these intangible investments is substantial and growing. The national accounts do not include the value of the resulting intangible assets creation as part of output and do not include the capital gains accruing to the owners of these intangible assets as income. As a result, a revised calculation of total factor productivity (TFP), taking into account these growing intangible investments, reveals quite a different picture of the US economy from that estimated by the conventional methodology. In particular, we find that the magnitude of intangible capital investments that accompany computerization of the economy is plausibly far larger than the direct investments in computers themselves. A revised estimate that takes intangible investments into account indicates that the TFP of the US economy grew up to 1% per year faster during the past decade than previously estimated.

"You can take my factories, burn up my buildings, but give me my people and I'll build the business right back again."

-- Henry Ford

1. Introduction

Managers and investors recognize that not all assets are tangible. Their real and financial investment decisions reflect this fact, although not all accounting measures do. Indeed, the most important assets in modern economies may well be poorly-measured intangible assets such as new business processes, firm-specific human capital, and managerial know-how. Like tangible assets, intangible assets are costly to create. Like tangible assets, they create a stream of expected benefits over a period of years. However, standard balance sheets, the national income accounts and traditional growth accounting do not treat tangible and intangible assets symmetrically.

In this paper, we modify the traditional growth accounting methodology to better account for intangible assets and empirically estimate their magnitude. In particular, we focus on computer-related intangible assets and find that they are quite large. This reflects the fact that the most pervasive technological change of this era has been the widespread computerization of many companies. The implications of our approach can address some of the recent puzzles regarding computers and productivity growth in the U.S. economy.

A number of researchers explored the linkages between computerization and productivity growth and some have focused on the importance of complementary organizational change.[1] In particular, David (1990) has drawn parallels with electrification of the economy a century ago and the large organizational changes needed to realize the full productivity benefits of electrical machinery. Similarly, Greenwood (1997), Greenwood and Jovanovic (1999), and Hobijn and Jovanovic (1999) take the diffusion lag hypothesis

[1] See for example Berndt and Morrison (1995), Brynjolfsson and Hitt (1993, 1996, 2000), David (1990), Gordon (2000), Griliches (1994, 1995), Lichtenberg (1995), Jorgenson (2001), Jorgenson and Stiroh(1995, 2000), Oliner and Sichel(1994, 2000), Triplett (1998). Brynjolfsson and Yang (1996) provide a literature review.

seriously, and suggest that not only the productivity slowdown after 1973 but also the apparent lackluster performance of stock markets in the 1970s may be explained by the "information technology revolution" brewing behind the scenes. Bresnahan, Brynjolfsson and Hitt (2001) find strong correlations between computerization and a cluster of organizational changes that affect, *inter alia,* labor demand, while Brynjolfsson and Hitt (2000) review a range of evidence supporting the thesis that the direct costs and benefits of computers are just the tip of a much larger iceberg of complementary organizational, process, and strategic changes.

The conceptual model economy in this paper is a simple combination of the neoclassical growth model and the q theory of investment. The explanation for the productivity slowdown and recovery is also a combination of mismeasurement and diffusion lag, but in a different sense. The mismeasurement proposed in this paper is mismeasurement of *capital output*, in particular the omission of intangible investments, and not the mismeasurement of *consumption outputs* such as new goods, conveniences, quality changes, etc., proposed by Griliches (1994) and Diewert and Fox (1997). In addition, this study also tries to identify a set of conditions under which an apparent productivity slowdown can be accounted for by a new technology diffusion lag; if it is a true diffusion lag and the financial markets value it correctly, then we should observe the higher market valuation for new technology investments.

The simple combination of growth accounting and the q theory of investment, two neo-classical approaches, has the potential to explain the following observations found in the literature, which are sometimes apparently contradictory to one another.

1. The coincidence of massive computer investments with the slowdown in measured TFP after 1973 in the US and other OECD countries.
2. The discrepancy between the casual observation of "computer age everywhere" and the relatively small proportion of computer capital in the national accounts.
3. The observed large excess marginal product of computers found in the micro data.
4. The surprisingly large valuation of computer capital found in the micro data.

Our basic argument is as follows. Conventional growth accounting does not take into account intangible investments such as the adjustment costs incurred during installation and the unmeasured investments complementary to computer technology. These unmeasured intangibles include training costs, organizational restructuring, business process redesign, and even the reallocation of decision rights and incentive systems. Computer systems both enable and demand wide-ranging changes in firms before they can be fully productive. Managers recognize this and devote large budgets to internal and external staff who develop and implement these changes. Furthermore, they recognize that the benefits from these changes will not be exhausted in a single year; on the contrary, the returns may take years to be fully realized. Thus, the costs are in a real economic sense, investments in intangible assets, not expenses associated with only current output. However, while Generally Accepted Accounting Principles calls for firms to capitalize purchases of computer hardware and some types of software, they treat almost all the costs of computer installation, business process development and investments in associated intangible assets as expenses. Firms' balance sheets generally do not reflect the value of a more efficient supply chain process, a more responsive customer service system, a faster product design cycle, or most of the other intangible investments that account for the majority of the costs of a new computer system. Similarly, the national accounts recognize neither the stock market appreciation as output nor the capital gains as income, and thus overlook the growth of these intangible assets. When the investment growth rate – the second derivative of capital stock - is low, or when the size of these intangibles is relatively small, then the conventional accounting works fine when it comes to estimation of the *rate* of output and productivity growth.[2] However, in the case of computer investments, the growth rate of investment has been 30% in real terms for the last three decades and the absolute size the computer-related intangibles is likely to be larger than the computer investments themselves..

[2] The current *level* of output may be underestimated when intangibles are ignored, but the growth *rate* is not significantly affected.

The effects of these omissions on growth accounting can be significant. While it is difficult to determine their exact magnitude, the complementary intangible investments may be up to ten times larger than the computer hardware investments themselves, and consequently, a non-trivial share of overall output (See Brynjolfsson and Hitt, 2000 for a review). The U.S. economy may have created over one trillion dollars worth of computer-related intangible assets over the past decade. These assets are part of the economy's output just as if they were factories made of bricks and mortar. However, they have been omitted from our national accounts and therefore the official statistics are likely to have underestimated total output and productivity growth significantly. In fact, our calculations suggest that their magnitude may be sufficient to eliminate much of the productivity slowdown after 1973.

In the next section, we will propose a revised growth accounting method, using a modified production function borrowed from the q-theory of investment. The basic model is based on Hayashi (1982), Wildasin (1984), and Hayashi and Inoue (1991). The analysis also draws on Hall (2001), particularly for the formalization of the idea that the market value of the firm can provide insight into the value of its intangible assets. This paper's contribution is in applying this now-familiar theory of investment to the computer productivity puzzle, including a derivation of the size of the TFP mismeasurement and an application of this theory to firm level data on computer investments. Section 2 provides the new derivation and in section 3, the result of TFP revision is applied to U.S. data. The final section concludes the paper with a discussion on its implications and directions for future research.

2. A Revision of TFP Measurement with the Investment Theory

A Brief Review of TFP Measurement and the Theory of Investment

Solow's (1957) growth accounting framework, based on his own neo-classical growth model (Solow, 1956,) has survived for more than four decades. Barro (1998) summarizes the framework in light of some recent relevant issues. Solow's growth decomposition starts with the neoclassical constant return to scale (CRS) production function:

(1) $Y = p\ G(K,N,t)$

where p is the price level of the output, K is the Jx1 vector of capital goods, and N is the Lx1 variable input vector. The production function is also a function of time t, which determines the productivity level at time t. Output growth can be decomposed as follows.

(2)
$$\begin{aligned} g_Y &= \dot{Y}/Y = p(G_K\dot{K} + G_N\dot{N} + G_t)/Y \\ &= \left(\frac{pG_K K}{Y}\right)\left(\frac{\dot{K}}{K}\right) + \left(\frac{pG_N N}{Y}\right)\left(\frac{\dot{N}}{N}\right) + \left(\frac{G_t}{G}\right) \\ &= \left(\frac{rK}{Y}\right)g_K + \left(\frac{wN}{Y}\right)g_N + g_T \\ &= s_K g_K + s_N g_N + g_T = (1-s_N)g_K + s_N g_N + g_T \end{aligned}$$

where the upper dot represents the total derivative with respect to time, the subscript K in G_K denotes the partial derivative with respect to K, and (r,w) are price vectors for (K,N). g_i denotes the growth rate of $i = Y, K, N$, and s_i the income share of $i = K, N$. The final term g_T is the growth rate of total factor productivity (TFP). The third line in (2) follows from the competitive factor markets assumption. The last equality comes from the first-degree homogeneity of G in (K,N), which is a direct consequence of CRS technology. Although presentation of the equations in (2) is for a one capital and one variable input case, the multiple good case is straightforward. For example, just replacing G_kK with a vector of which the i-th element is $G_{K_i}K_i$, and g_i also with a vector, and denoting two consecutive vectors as the dot product suffice for the multiple good case presentation of the equations in (2).

Note that investment behavior is not considered anywhere in conventional growth accounting. The technology outlined above assumes that capital services can be treated just like variable inputs: the firm can buy them from the spot market and install them without any friction. However, casual observation tells us that capital investment usually requires more than just buying or renting capital goods; the installation of new equipment takes time and additional costs (See e.g. Berndt and Fuss, 1986).

To incorporate this observation, Lucas (1967) introduced the following production function, taking into account "adjustment costs" of capital installation:

$$Y = pF(K,N,I,t)$$

The production technology is assumed homogenous of degree one with respect to capital *(K)*, investment *(I)*, and variable inputs *(N)*. The first-degree homogeneity here differs a bit from constant returns to scale in the usual sense: doubling *(K,N)* without doubling investment *(I)* results in a more than doubling of *F*, while doubling *(K,N,I)* will double *F*. The total costs of investments of one unit of capital goods are now $(z - pF_I)$, where *z* is the market price of the capital goods, and $-pF_I$ is the marginal adjustment costs with F_I a first derivative with respect to *I*. *F* is assumed non-increasing and concave in *I*, reflecting the fact that adjustments are disproportionately costly as the investment increases.

Using essentially the same production function as Lucas's(1967), Hayashi (1982), Wildasin (1984), and Hayashi and Inoue (1991) derived the relationship between the market value of firms and the investment behavior. Brynjolfsson and Yang (1999) estimate the shadow values of different capital goods using the same framework. The representative price-taking firm of the economy faces the following optimization problem.

$$\underset{I,N}{Maximize}\ V(0) = \int_0^\infty \pi(t)u(t)dt$$

$$\text{where}\quad \pi(t) = pF(K,I,N,t) - w^t N - z^t I$$

$$\text{given}\quad \frac{dK_i}{dt} = I_i - \delta_i\ K_i, \text{ for all } i = 1, 2, \ldots, J.$$

Again, *(K,I)* are the *J*x*1* vectors of capital goods and their investments, and *N* is the *L*x*1* variable input vector. The firm maximizes the current market value *V(0)*, which is the sum of current value profits at time t, $\pi(t)$, discounted by *u(t)*. In turn, the profit is the output, *pF(K,I,N,t)*, less the input costs, $w^tN + z^tI$; where *(p, w, z)* are prices of output, variable inputs and capital goods, respectively. As for the vector notation, w^tN represents the dot product.

The rate of change in K_i is given by the current flow of investments less depreciation of existing capital stock, $\delta_i K_i$, where δ_i denotes the depreciation rate. *F(K,I,N,t)* is also assumed non-decreasing and concave in *K* and *N* , and non-increasing and convex in *I*. This assumption together with the first-degree homogeneity of *F*, guarantees the Mangasarian (1966) sufficient conditions, which state that the first order necessary conditions of the following hamiltonian suffice to yield the global maximum.

$$H(I,K,N,t) = (pF(K,I,N,t) - w^t N - z^t I)u(t) + \sum_{i=1}^{J} \lambda_i (I_i - \delta_i K_i)$$

From the maximum principle the following conditions are straightforward:

$$\frac{\partial H}{\partial \lambda_j} = \dot{K}_j = I_j - \delta_j K_j \qquad \forall\, j = 1,2\ldots J \text{ and } \forall t \in [0,\infty]$$

$$\frac{\partial H}{\partial K_j} = -\dot{\lambda}_j = pF_{K_j} u - \lambda_j \delta_j \qquad \forall\, j \text{ and } \forall t$$

(3) $$\frac{\partial H}{\partial I_j} = 0 = (pF_{I_j} - z_j)u + \lambda_j \qquad \forall\, j \text{ and } \forall t$$

$$\frac{\partial H}{\partial N_i} = 0 = (pF_{N_j} - w_i)u \qquad \forall\, i = 1,2,\ldots,L \text{ and } \forall \text{t}$$

$$\lambda(\infty)K(\infty) = 0$$

One of interesting feature of the solution is a myopic investment decision - equating the capital market's excess valuation of capital with the firm's adjustment costs - is the unique optimal strategy under the efficient market hypothesis. Exploiting the first degree homogeneity of F, the following market value decomposition can be derived from these conditions, and can be econometrically estimated using the variation across firms and across time.[3]

(4) $$V(0)=\sum_{j=1}^{J}\lambda_j(0)K_j(0)$$

TFP Measurement and the Investment Theory

Here we need to clarify our interpretation of "adjustment costs" of Lucas(1967) and Hayashi(1982) in the context of national accounting, and in view of our definition of intangible investments. According to the early literature, adjustment costs are foregone output, which cannot be avoided when firms invest in valuable capital goods. Especially convexity of adjustment costs is assumed to guarantee a unique solution to the above-stated firm's problem. Our interpretation goes further without violating crucial mathematics and economics of the original interpretation. In particular, we include "intangible correlates" and show that under some reasonable assumptions the mathematics and economics of intangible correlates behave the same way as the adjustment costs do.

To see this clearly, let's consider the following national account identities using our modified production function:[4]

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[3]
$$\begin{aligned}\because\quad \sum_{j=1}^{J}\lambda_j(0)K_j(0) &= \sum_{j=1}^{J}(\lambda_j(0)K_j(0)-\lambda_j(\infty)K_j(\infty))\\
&=\sum_{j=1}^{J}\int_0^{\infty}(-\dot{\lambda}_jK_j-\lambda_j\dot{K}_j)dt=\sum_{j=1}^{J}\int_0^{\infty}(pF_{K_j}K_j+pF_{I_j}I-z_jI_j)u(t)dt\\
&=\int_0^{\infty}\left(\sum_{j=1}^{J}(pF_{K_j}K_j+pF_{I_j}I-z_jI_j)+\sum_{i=1}^{L}(pF_{N_i}N_i-w_iN_i)\right)u(t)dt\\
&=\int_0^{\infty}\left(pF(K,I,N,t)-z'I-w'N\right)u(t)dt\\
&=V(0)\end{aligned}$$

[4] The third equality is due to the homogeneity of degree one, and the final equality came from the third of the first order conditions in equation (3).

$$\xi C + zI = Y = pF(K,I,N) = pF_N N + pF_K K + pF_I I = wN + rK + (z\text{-}\lambda)I$$

Gross Domestic Product (GDP) denoted $Y = pF(\cdot)$ is measured as the sum of consumption good production (ξC) plus investment good production (zI). Here p is the price of output – GDP deflator, ξ and z are prices of consumption goods and capital goods respectively.

These identities imply that the true national income ($wN + rK$) is devoted to consumption (ξC), measured investment (zI), and unmeasured investment $(\lambda\text{-}z)I$.

$$wN + rK = \xi C + zI + (\lambda\text{-}z)I = Y + (\lambda\text{-}z)I$$

The term, $(\lambda\text{-}z)I$, is the portion of personal income spent on producing capital goods that are not measured by national accounts, because the national accounts measure only zI, not the whole λI. In short, in the context of national accounting the *adjustments costs are nothing but unmeasured production of investment goods;* the economy's true investment is λI, not zI.

Our definition of intangible investment is exactly this term, $(\lambda\text{-}z)I$, which plays the same economic role as measured investments (zI), but does not appear anywhere in the national accounts unlike their measured counterparts. One thing to note here is that our definition is conceptually broader than the definition of adjustment costs in the traditional literature, which in general confines adjustments costs to installation and adoption costs of new capital goods. On the other hand, our definition includes any investments on complementary goods which are not measured by national accounts.

To see this clearly, let us conduct a simple conceptual experiment that shows that adjustment costs and other intangible investments are mathematically equivalent. For simplicity, define a specific form of adjustment cost function in which it takes the form of foregone output.

(3)′ $Y = pF(K,N,I,) = p(E(K,N)-H(I,K))$

$E(K,N)$ is the production function, and $H(I,K)$ is the adjustment cost function, defined by Lucas(1967) and Hayashi(1982). Hayashi suggested, as an example, a Cobb-Douglas form of adjustment cost function, $H(I,K) = c_1 I(I/K)^{\gamma}$, $\gamma>0$. Instead, we conceptually divide $H(I,K)$ into Hayashi's adjustment costs, $\Gamma(\cdot)$, and correlated intangible investments, $B(I)$. Again for simplicity, let us assume that this intangible correlates are perfect complementary to tangible investments, then we have the following relationship.

$$H(I,K) = \Gamma(I,K) + B(I) = c_1 I(I/K)^{\gamma} + c_2 I$$

Notice the first degree homogeneity still holds in equation (3)′, so does the hamiltonian of the firm's problem, when we assume that the intangible capital depreciates at the same rate with its tangible counterpart. All other conditions and results remain as they were. The only change is the interpretation of the shadow value. Explicitly writing out one of the first order conditions, we have

$$\lambda = z - pF_I = z + pH_I = z + p(\Gamma_I + \mathrm{B}_1) = z + pc_1(1+\gamma)(I/K)^{\gamma} + pc_2$$

In other words, the shadow value is the sum of the price of the capital good, the marginal adjustment costs, and the necessary intangible investments for a dollar worth of tangible investments. Notice that although the interpretation changes, the mathematics to derive the firm's problem, its hamiltonian, and the first order conditions holds as they were. Another interpretation is that the intangible correlates are nothing but the linear component of adjustments costs.

An important aspect of our interpretation needs to be clarified. Under our framework, current intangible investments, $- pF_I = (\lambda-z)I$, are not counted in the national accounts, but the value of the economy increases by this exact amount of intangible investments, as the investments are expected to bring future capital income. In other words, capital owners get the benefits of these investments as a form of capital gains, which is not counted as GDP, not as a form of dividends, which would be counted as GDP. For instance, if Bill Gates builds a factory and is paid a wage for laying the bricks, then the value of the factory and the value of his wages would be part of GDP. However, if Bill Gates creates a billion dollars worth of intangible assets for Microsoft and is "paid" via capital gains in his equity in Microsoft instead of current salary, then neither the intangible assets nor the capital gains are included as part of traditional GDP; only his actual salary at Microsoft ($639,000 in 2000) and any dividends on Microsoft stock ($0 in 2000) would be included. An interesting prediction of our interpretation is that if the relative size of intangible investments grow year after year then by the traditional measure the ratio of capital gains to measured output grows, too.

Now let us turn to the revision of growth accounting. When the technology follows the rule given in equation (2), the growth decomposition should be revised as follows:

$$g_Y = \dot{Y}/Y = p(F_K\dot{K} + F_N\dot{N} + F_I\dot{I} + F_t)/Y$$

From one of the first order conditions in (3), the shadow value of K_j at time t is given as the unit price of capital good plus the adjustment costs. Hence we can link the unobservable adjustment costs to the observable shadow values.

$$\lambda_j(0) = (z_j - pF_{I_j})u(0) = \ (z_j - pF_{I_j})$$

The growth decomposition now becomes:

$$g_Y = \left(\frac{pF_K K}{Y}\right)\left(\frac{\dot{K}}{K}\right) + \left(\frac{pF_N N}{Y}\right)\left(\frac{\dot{N}}{N}\right) + (1-\frac{\lambda}{z})\left(\frac{zI}{Y}\right)\left(\frac{\dot{I}}{I}\right) + \left(\frac{F_t}{F}\right)$$

The presentation above is for the single capital good case. The same presentation holds, when we replace $F_K K$ and $\dot{K}/K$, for example, with vectors of which the j-th elements are $F_{K_j} K_j$ and $\dot{K}_j / K_j$, respectively. The new term absent in the conventional growth accounting is the third term, $(1-\lambda/z)\left(\frac{zI}{Y}\right)g_I$. Observe that the term is negligible if the shadow value of capital is close to its price, ($\lambda = z$), or if either the investment income share (zI/Y) or the growth rate of investment (g_I) is small. In particular, when the shadow value of a unit of good equals its price ($\lambda = z$), then the third term vanishes and there is no need to correct the conventional framework of the growth decomposition.

Let us reiterate the interpretation of the above output decomposition using difference representation for simplicity:

$$\Delta Y = p\left(F_K \Delta K + F_N \Delta N\right) + (z-\lambda)\Delta I + pF_t \Delta t$$

Whenever the observed shadow value of a capital good is larger than the market price of the good ($\lambda > z$) and the investment growth rate is positive ($\Delta I > 0$), then we can conclude that the economy is producing intangible investment goods, the total size of which is $(\lambda - z)\Delta I$. The conventional output growth measure (ΔY) does not properly capture these investments but treats them as expenses necessary only for current production, while in fact the intangible investments will be productive in the future. The conventional method is benign when the adjustment costs are negligible or the investment *rate* (ΔI not I) is not changing. If neither holds, however, an appropriate correction is needed. In particular, omitting the accelerating investments will result in the underestimation of both output growth rates and TFP growth rates. In sum, conventional growth accounting fails to capture the effects of intangible investments when these investments are growing.

To help the discussion in the next subsection, let us write out the growth decomposition explicitly for a case of two capital goods: non-computers (K_n, I_n) and computers (K_c, I_c). Here we assume the competitive factor market and introduce the income share of each good, and denote it $s_g = pF_g / Y$, for good g. In addition, we define intangible investment share of output, $\beta_j = (\lambda_j / z_j - 1)\left(\frac{z_j I_j}{Y}\right)$, for $j = n, c$. New growth decomposition now becomes:

$$\begin{aligned} g_Y &= s_{K_n} g_{K_n} + s_{K_c} g_{K_c} - \beta_n g_{I_n} - \beta_c g_{I_c} + s_N g_N + g_{TFP} \\ &= s_K g_K - \beta_n g_{I_n} - \beta_c g_{I_c} + s_N g_N + g_{TFP} \end{aligned}$$

where $K = K_n + K_c$. The second line, a Tornqvist aggregation, is introduced to compare the new TFP calculation with the conventional methods after adjusting income share of each input. As the share of labor services, $s_N = \frac{pF_N N}{Y}$, is obtained from directly observed employment and wage data, it will not change in the new framework. On the other hand the new capital share, $s_K = \frac{pF_K K}{Y}$ is different from the one estimated by conventional framework, because the capital productivity of conventional method does not take into account adjustment costs, which leads to underestimation. Fortunately for our purposes, we may set the capital share equal to $s_K = (1 + \beta_n + \beta_c - s_N)$, because production function is homogenous in the first degree. Remembering $s_{K,old} = 1 - s_{N,old}$ and $s_{N,old} = s_{N,new}$, we have the relationship between the old capital share and the new one, i.e. $s_K = (s_{K,old} + \beta_n + \beta_c)$. The amount $(\beta_n + \beta_c) g_K$ is the enhanced portion growth contribution of total capital coming from capitalized intangible investments.

Hence, output decompositions by the old framework and new one can be summarized as follows:

$$\begin{aligned} g_Y &= s_{K,old} g_K + s_N g_N + g_{TFP,old} = s_K g_K - \beta_n g_{I_n} - \beta_c g_{I_c} + s_N g_N + g_{TFP} \\ &= (1 - s_N + \beta_n + \beta_c) g_K - (\beta_n g_{I_n} + \beta_c g_{I_c}) + s_N g_N + g_{TFP} \\ &= s_{K,old} g_K + s_N g_N + (\beta_n + \beta_c) g_K - (\beta_n g_{I_n} + \beta_c g_{I_c}) + g_{TFP} \end{aligned}$$

Comparing the first and the last equality we have the difference between the revised TFP and the conventional TFP:

$$(5)\ g_{TFP} - g_{TFP,old} = \beta_n(g_{I_n} - g_K) + \beta_c(g_{I_c} - g_K) = (\beta_n g_{I_n} + \beta_c g_{I_c}) - (\beta_n + \beta_c)g_K$$

The first term of the second equality represents the growth contribution of intangible investments, and the second term does the underestimated portion of capital productivity in the conventional measure. If we explicitly treat intangible investments - the foregone output - as output, we can write out the above equations as follows:

$$\begin{aligned} g_Y + (\beta_n g_{I_n} + \beta_c g_{I_c}) &= (1 - s_N + \beta_n + \beta_c)g_K + s_N g_N + g_{TFP} \\ &= s_{K,old} g_K + (\beta_n + \beta_c)g_K + s_N g_N + g_{TFP} \end{aligned}$$

In this formulation, g_Y is the measured output growth rate, $(\beta_n g_{I_n} + \beta_c g_{I_c})$ unmeasured investment output of the intangible investments, and $(\beta_n+\beta_c)g_K$ is the enhanced portion of growth contribution coming from capitalized intangible investments.

3. Estimation of the New TFP

Measuring the Shadow Value of Capital Goods

According to equation (5), the revision of TFP boils down to 1) estimation of shadow values (λ/z, Tobin's q value) of capital goods, 2) the income share of investments, and 3) the growth rate of investments. The latter two are readily available from the government data. For our estimates of the shadow value of capital goods, we will rely mainly on a study of Brynjolfsson and Yang (1999), who estimated the different shadow values for different capital goods. Using a dataset of 820 US non-financial firms, they concluded that the shadow value of computer capital was at least five in the period of 1987-1994, while the value for other types of capital is about one.

Table 1 reproduces their results. The point estimates of the q $(= \lambda/z)$ value for computers range from 5.6 in a fixed effect within model to 20.3 in a between model. The q values for other types of capital are close to unity, as the original q theory without adjustment costs predicts. Detailed discussion on the sources of the surprisingly large q value for computers is in Brynjolfsson and Yang (1999), and also in Brynjolfsson, Hitt, and Yang (1999). According to their discussion, the high shadow value of computers reflects the complementary investments in software, training, business process redesign, and the re-organization toward new organizational forms, often involving more distributed decision-making structures.

Table 2 provides further evidence of the large intangible investments associated with computers. In a typical enterprise resource planning (ERP) system, the computer hardware costs amount to less than $1 million, while the internal and external costs of deploying the new information system exceed $20 million. The majority of these additional costs are not recurring and can be properly thought of as investments in various intangible capital assets, such as new business processes and firm-specific human capital. More generally, the spending of American firms on internal and external computer services for development and installation of computer-related business processes greatly exceeds the direct spending on computer hardware itself, although only that latter is typically included as an asset on firms' balance sheets. In the system of national accounting, the wages of internal and external staffers to build intangible assets are counted (wN). However, unlike tangible investments these expensed wages reduce capital's measured current profit (rK) by the same amount, and thereby result in a net undercounting of the combined income. However, if the financial markets value the combination of computers and intangibles correctly, the econometric estimation of the value decomposition equation (4) should identify these hidden assets.

The estimates by Brynjolfsson and Yang rely on data from financial markets regarding the market value of firms and, implicitly, their tangible and intangible assets. For our purposes, one must handle these estimates with caution, as they represent private returns which may be quite different from the aggregate social returns on computers. The aggregate returns may be lower or higher than the private returns. If the high private valuation of computer-associated intangible assets result from the destruction of rival firms' assets, then the aggregate effect should be smaller. For example, the computer investments of Wal-Mart's efficient logistic system may destroy the value of the intangible assets of many local shops.[5]

On the other hand, there may be positive externalities as well. For example, the methods of computer pioneers, including Wal-Mart, are widely studied and imitated in a variety of industries. Indeed, some of Wal-Mart's managers, who had developed and operated its efficient computer-based logistic system, were subsequently hired by Amazon.com, bringing their newly-created human capital with them. The positive externalities of computers and their connections may be quite large (Bresnahan and Trajtenberg, 1995), particularly with respect to network effects (e.g. Economides, 1996). In this case, the aggregate effect would be higher than the private returns.

Furthermore, although the shadow value of computer capital during the estimated period, 1987-1994, was stable, there are reasons why it may fluctuates over time. It may bigger during initial stages of investment take-off, and may taper off later on. To capture these considerations, we lay out in tables 3, 4 and 5 the different effects of the TFP revision on various *q* values of computers. In addition, we provide a backward calculation experiment; estimating implied shadow value of computer capital that could have maintain the same TFP growth rate for the last half century the rate of 1948-1973 period.

The Revised TFP

The most recent TFP calculations for the U.S. economy are by the Bureau of Labor Statistics (BLS, 2001) and Jorgenson and Stiroh (2000), Jorgenson (2001), and Oliner and Sichel (2000). Oliner and Sichel (1994) and Jorgenson and Stiroh (1995) pioneered

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[5] The computer investments may also destroy the value of accumulated intangible assets using pre-computer technologies at Wal-Mart itself. However, our method already accounts for this destruction; the market values reflect the <u>net</u> changes in intangibles associated with computerization.

the estimation of the contribution of computers to economic growth. Oliner and Sichel's earlier paper (1994) concluded that since the computer share, including software, was still small in the economy, and then the contribution to growth was likely to be relatively small, too.[6] More recent work by Oliner and Sichel (2000) and Jorgenson and Stiroh (2000) shows that the recent productivity rebound after the mid-nineties can largely be attributable to the TFP growth in the computer-producing sector and the computer capital deepening in the computer using-sectors.[7] Yet if the additional intangible investments are taken into account, the picture may look quite different.

The upper part of table 3 shows Jorgenson's TFP estimation. Jorgenson (2001) identified TFP growth 0.61% per annum during the period of 1948-1999. While the TFP of the whole economy grew 0.92% per year during the earlier part of the last half century (1948-1973), its annual growth rate dropped to about 0.25% during the period of 1973-1995. The rebound of its annual growth rate to 0.75% after 1995 approached but still did not exceed the pre-1973 level of growth.

The upper part of table 4 summarizes the BLS's estimates. According to the BLS report, the TFP of the US private sector grew 1.4% per annum during the latter half of the century from 1948 to 1999. During the third quarter of the century (1948-1973) it grew 2.1% per annum, and during the last quarter of the century (1973-1999) growth slowed down to 0.8% per annum. Especially for the period of 1973-1995, TFP grew mere 0.6%

[6] These studies deduced that the computers' contributions to output growth accounted for at most 0.3 of a percentage point for the last three decades, and that this growth came from the rapid investment rather than from any productivity increase. Oliner and Sichel (1994) concluded that since the computer share of total capital stock was still only about 2%, however productive computers were, they could not meaningfully boost economy-wide productivity. They argued that the resolution to the Solow productivity paradox was that "you don't see computers everywhere, in a meaningful economic sense." (Triplett, 1998).

[7] This literature indicates that the recent productivity rebound is largely due to the sharp price decline of computers and also to the rapid growth in computer investments. According to the calculation of Jorgenson and Stiroh (2000) and Jorgenson (2001), growing investment in computers accounted for about a half percentage point increase in average labor productivity, and a price decline of computers for two-thirds of a percentage point in the aggregate TFP. Oliner and Sichel (2000) conclude that the combination of the "production" of computers and the "use" of them accounted for most of the productivity surge after 1995. Gordon (2000) provides a

per year, and the rebound after 1995 still fell short of the growth rate during the period of 1948-1973. The well known productivity slowdown after 1973 is again apparent, even after the recent revisions of the government statistical agencies.

During the same period of 1973-1999, real computer investments grew rapidly, at about 30% per annum. In comparison, real total private capital investment, including computers, grew a mere 2.66% during the same period. During the previous period of 1948-1973, that growth rate was 4.14%. The nominal share of computer investment in GDP also quadrupled from 0.34% to 1.32% in the 1973-1997 period. This is the essence of the famous Solow's Computer Paradox (Solow, 1987): in expectation of greater productivity, firms invests heavily in computers, but overall measured productivity nonetheless slows down considerably, at least initially.

Let us discuss our findings. Since the estimated shadow value of non-computer capital in table 1 is close to unity, the revision of the TFP as in equation (5) now becomes:

$$(6) \qquad g_{TFP} - g_{TFP,old} = (\lambda_c / z_c - 1)(z_c I_c / Y)(g_{I_c} - g_K)$$

There is a slight problem to use equation (6) directly, because our estimates for $(\lambda_c / z_c - 1)$ includes software components, which NIPA already revised to treat as investments. To correct this, we use the following equation to take back the software portion of our shadow value, denoted with the subscript *s*.

$$(7) \qquad g_{TFP} - g_{TFP,old} = ((\lambda_c / z_c - 1) z_c I_c - z_s I_s) / Y)(g_{I_c} - g_K)$$

The left panel of table A provides times series of this TFP revision using data from Jorgenson (2001) and BEA (2001); and the center panel is the time series of $((\lambda_c / z_c - 1) z_c I_c - z_s I_s) / Y) g_K$, which summarizes underestimated portions of growth

dissenting view, giving heavier weight to cyclical factors, while acknowleding the important role of productivity growth in the manufacturing of computers.

contribution of capital when investments in intangible assets are ignored. The sum of corresponding columns of the two panels represents the size of intangible assets unmeasured in the conventional growth accounting, and is provided in the right panel. When preparing table A, we use BEA data for computer investments (z_cI_c) and for their growth rates g_{I_c} ; and Jorgenson (2001) for output (Y), and growth rate of capital services (g_K).

An example of these calculations are shown in table B. In 1996, real output of the US economy grew from $8.057 trillion to $8.339 trillion, which is 3.38% as a percentage of 1996 output. Jorgenson's (2001) attributed 2.43% ($196.3 billion) to factor accumulation and 1.06% ($85.7 billion) to TFP growth. Our revised method when λ/z = 5, added 0.82% ($68.44 billion) worth of intangible investments to output, and attributed 0.07% ($5.9 billion) more to the contributions from factor inputs. As a result in the new framework, the TFP growth rate increased by 0.75% (from 0.63% to1.81%).

We report the revised TFP for the period of 1948-1999, based on earlier estimations by Jorgenson (2001), Bureau of Labor Statistics (BLS, 2001), and, in turn, by Oliner and Sichel (2000). The lower part of table 3 summarized our revision of TFP growth based on Jorgenson (2001). As the estimates are most sensitive to the choice of the shadow value (λ/z), we present several cases of the value, ranging from 3 to 10. For λ/z = 10, which is the middle of the range of values found in Brynjolfsson and Yang (1999), TFP slowdown is not evident in the revised framework. If anything, the average TFP growth rate during the final quarter of the century (1973-1999) is no less smaller than that of the third quarter of the century (1948-73). Interestingly, in recent years TFP may have actually accelerated above the level of pre-1973 era once one includes the value of computer-related intangible assets created during this period.

The lower parts of table 4 and 5 present TFP revisions based on BLS (2001) and Oliner and Sichel (2000). When preparing times series for equation (6), we use BEA data for computer investments (z_cI_c), their growth g_{I_c} , and output (Y); and BLS data for growth rate of capital services, g_K, in order to maintain consistency with authors' data. The lower parts of table 4 and 5 are results of our revision according to equation (6) with different λ/z values. Our numbers again tell a different story about the postwar U.S. economy. If $\lambda/z = 10$ during the period of 1973-1990, then more than 2/3 of productivity slowdown vanishes.

However, interpreting the new TFP numbers calls for a caution, as our estimation of shadow value (λ/z) is based on private returns for computer capital in large corporations during the period of 1987-1994 period only. First, it may well be the case that the shadow value of computer may have been dropping over time as workers and managers get more experience with computers and as organizations and institutions evolve to systematize the introduction of computer-based methods. To take into account these considerations, in table 3 we provide several revised TFP figures according to different shadow values ($\lambda/z = 3, 5, 10$). In the last row of the table, we present a result of backward calculation: in the period of 1973-1990, if the shadow value of computer capital were 8.3, then the economy's productivity growth would been a consistent 1% per year, which was pre-1973 level. For recent years after 1995, the shadow value of around 3.5 is enough to boost the TFP growth to exceed the pre-1973 level. Finally, Figure A draws TFP level trends for the period of 1949-1999, plotting the effects of alternative shadow values of computer investments; the base year is 1960, when computer investment began to be recorded.

4. Discussion and Conclusion

Let us discuss the questions raised in the introduction one by one.

1. The coincidence of the TFP slowdown and massive computer investments.

As shown in tables 3, 4 and 5, measured TFP and output seem to slow down by conventional calculations. However, according to our revised calculations, TFP does not slow down significantly, even though *measured* output growth slows down more than 1% after 1973 before 1995. Interestingly, the upward trend in the productivity growth rate after 1995 exceeds the growth rate before 1973, the year the apparent slowdown started. The difference between TFP growth and output growth reflects our hypothesis of foregone output during the adjustment process. As business firms were willing to forego output during the investment activity in order to capture the benefits later, the measured output growth was lower during the heavy investment period even if productivity of the economy remains the same. Alternatively, one could count the creation of intangible assets as a contribution to output, in which case total output growth would not have been any lower during this period.

2. The discrepancy between the perception that "we see computers everywhere" and the relatively small proportion of computers as measured in the national accounts.

According to the 1999 December issue of the Survey of Current Business (BEA, 1999), computer hardware investment comprised 1.1% of GDP in 1998. The software that started being included in that issue encompassed 1.4% of GDP. This paper's estimation of the investments in computer-related intangible assets (including software) is up to ten times greater than the computer hardware. Thus, the 1998 investments in computer-related assets, tangibles and intangibles combined, may have constituted as much as 10% of GDP. According to this calculation, more than a third of total investment in nominal terms are being poured into computer-related activities. In light of this, it is not surprising that there is a perception that we see the effects of computers everywhere. Even back in 1987, the year of Solow's famous quip, we estimate that computer hardware and its complementary intangible investments may have been equal to about 7.5% of GDP, if the 10 to 1 ratio found by Brynjolfsson and Yang (1999) for a sample of 753 large firms held throughout the economy.

3. The observed excess marginal product of computers found in micro studies.

Following Hayashi (1982) and Wildasin (1984), we can write the production technology as follows:

$$Y = p\ F(K,N,I) = p(E(K,N) - H(I,K))$$

Here the adjustment cost function H explicitly takes the foregone output form. The adjustment cost function is increasing and convex in I, and decreasing in K. The observed marginal product of capital is:

$$Y_K = pE_K - pH_K$$

The first term is the normal return on capital and can be equated to the price of the capital goods, and the second positive term $-pH_K$ is the return on intangible investments that have been accumulated during the past investment process. In other words, the apparent excess marginal product of computers is in fact the normal return on intangible investments, which the conventional accounting books as expenses. A more detailed discussion on this issue is also found in Brynjolfsson and Yang (1999).

4. The large stock market valuation of computers

A firm with a large quantity of computer hardware installed also will typically have a large quantity of associated intangible assets, including capitalized adjustment costs. This should be reflected in its stock market valuation, even if these assets are not reflected on the firms standard balance sheet.

Algebraically,

$$\lambda/z = 1 - pF_I$$

The stock market's valuation for the computer capital installed in the firm is more than its acquisition cost, z, because it also reflects the value of associated intangible assets. There have been unusually high levels of real investment in computer equipment. If adjustment costs are convex, this will lead to unusually high levels of capitalized adjustment costs. In addition, computers are associated with extensive complementary investments in human capital and organizational change (e.g. Bresnahan, Brynjolfsson and Hitt, 2000, Autor, Levy and Murnane, 2000). The market valuation of past intangible investments can explain the large valuation. The paper by Brynjolfsson and Yang (1999) discusses this issue in detail.

Our “intangible investment” hypothesis may help explain some of the puzzles raised in the recent productivity literature concerning computer investments. While the proposed theory can account for the signs of the corrections needed, the exact magnitudes of the corrections depend heavily on the estimated value of the size of the intangibles. However, there is strong evidence that the size of these intangibles are large enough to make a material difference in the estimated productivity growth rates of the U.S. economy in recent years. If the size of intangibles is indeed growing relative to the rest of the economy, then traditional GDP and growth accounting may provide an unnecessarily misleading impression of the state of the economy. Future research should address this size issue more carefully, adopting more comprehensive data both in cross section and time series. In addition, industry-level and country-level studies may shed more light on intangible investment size.

Table 1. Effects of Various Assets on Firms' Market Valuation
Baseline Regressions of Different Models

Market Value	Pooled OLS	Fixed Effect Within w/Year	Fixed Effect Within wo/ Year	Between OLS
Computer Capital	16.391*** 1.271	5.616*** 0.902	6.876*** 0.913	20.334*** 3.001
Physical Capital	0.974*** 0.021	1.134*** 0.054	1.227*** 0.053	0.957*** 0.037
Other Assets	0.685*** 0.009	0.826*** 0.012	0.826*** 0.012	0.660*** 0.019
Controls	R&D** Adv Year*** Industry***	R&D Adv Year*** Firm***	R&D Adv Firm***	R&D Adv Industry***
R^2	0.8727	0.9704[A]	0.9711[A]	0.8740
Observations	4620	4620	4620	4620

Key: * - p<.1, **- p<.05, *** - p<.01

A: Excluding fixed effect variance when calculating R^2, R^2 = 0.723, 0.716 for fixed effect models.

Source: Brynjolfsson and Yang (1999)

Table 2. Typical Start-up Cost Structure for an Enterprise Resource Planning (ERP) Suite

Start-up Costs		$millions
Hardware	Application, Web, and database servers including storage	$0.8
Software	ERP application Suite License (HR, Financials, Distribution) 1,000 regular trained users, 2,000 casual users	$3.2
Implementation And Deployment	9 months to complete pilot site including process engineering, apps configuration, and testing 30 external consultants as $1,200 a day 30 internal staffers at an average salary of $100,000 3 additional external consultants at 9 sites for 3 months 9 additional internal staffers at each site for 6 month 5 days of user training at an average burdened user salary of $50,000 3 full-time training staff at an average burdened salary of $100,000	$16.5
Start-up Costs Total		**$20.5**
Ratio of IT Hardware to total Start-up costs		**26:1**

These figures do not include management time selecting, designing and managing implementation, including the modification of business processes, nor does it include staff time informally learning to use the system or modifying business processes to work with system.

Source: Gormely et al. (1998) and Authors' Calculations

Table 3: TFP Revision Based on Jorgenson (2001)

	1948-99	1948-73	1973-90	1990-95	1995-99
Output Growth	3.46	3.99	2.86	2.36	4.08
Contribution of Capital					
Non-Computers	1.56	1.9	1.25	0.87	1.51
Computers	0.15	0.04	0.20	0.22	0.55
Contribution of Labor Input	1.14	1.13	1.16	1.03	1.27
Aggregate Total Factor Productivity	0.61	0.92	0.25	0.24	0.75
Missing TFP					
When λ = 3	0.087	0.039	0.140	0.076	0.132
5	0.276	0.097	0.377	0.325	0.718
10	0.749	0.243	0.970	0.950	2.181
Revised TFP Growth					
When λ = 3	0.697	0.959	0.390	0.316	0.882
5	0.886	1.017	0.627	0.565	1.468
10	1.359	1.163	1.220	1.190	2.931

Implied shadow values when TFP growth maintains 1% per year

λ =			8.320	8.494	3.395

Source: Jorgenson (2001) and authors' calculation

Table 4: TFP Revision Based on BLS Estimates

	1948-99	1948-73	1973-79	1979-90	1990-95	1995-99
Output per hour	2.5	3.3	1.3	1.6	1.5	2.6
Contribution of capital intensity	0.8	1.0	0.7	0.8	0.5	1.0
Contribution of labor composition	0.2	0.2	0.0	0.3	0.4	0.3
TFP	1.4	2.1	0.6	0.5	0.6	1.3
Underestimated TFP						
3	0.11	0.05	0.11	0.22	0.10	0.17
5	0.35	0.13	0.33	0.58	0.43	0.91
10	0.96	0.32	0.86	1.49	1.24	2.75
Revised TFP						
3	1.51	2.15	0.71	0.72	0.70	1.47
5	1.75	2.23	0.93	1.08	1.03	2.21
10	2.36	2.42	1.46	1.99	1.84	4.05

Implied shadow values under the assumption TFP growth maintains 2% per year

			15.2	10.1	11.0	4.4

Source: BLS (2001), and author's calculation

Table 5: TFP Revision Based on Oliner and Sichel (2000)

	1974-90	1991-95	1996-99
Growth rate of output	3.06	2.75	4.82
Contribution of capital intensity	1.35	1.01	1.85
Contribution of labor	1.38	1.26	1.81
TFP	0.33	0.48	1.16
Underestimated TFP			
3	0.19	0.12	0.14
5	0.51	0.53	0.87
10	1.31	1.54	2.69
Revised TFP			
3	0.52	0.60	1.30
5	0.84	1.01	2.03
10	1.64	2.02	3.85

Implied shadow values under the assumption TFP growth maintains 2% per year

	12.4	9.9	4.9

Source: Oliner and Sichel (2000) and authors' calculation

Table A: Revised TFP and Intangible Investments

	Underestimated TFP Growth			Underestimated Capital's Contribution to Growth			Computer Related Intangibles' Contribution to Growth		
	shadow values			shadow values			shadow values		
	3	5	10	3	5	10	2	5	10
Year									
1949	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1950	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1951	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1952	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1953	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1954	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1955	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1956	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1957	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1958	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1959	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1960	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1961	0.042	0.105	0.262	0.006	0.014	0.035	0.048	0.119	0.298
1962	0.026	0.065	0.163	-0.004	-0.009	-0.023	0.022	0.056	0.140
1963	0.167	0.402	0.988	0.003	0.007	0.018	0.171	0.409	1.006
1964	0.066	0.157	0.385	0.012	0.029	0.072	0.078	0.186	0.457
1965	0.089	0.214	0.528	0.015	0.035	0.086	0.103	0.249	0.614
1966	0.177	0.428	1.055	0.016	0.039	0.095	0.193	0.466	1.150
1967	0.051	0.126	0.312	0.040	0.097	0.242	0.091	0.223	0.554
1968	0.043	0.109	0.274	-0.003	-0.007	-0.018	0.041	0.102	0.256
1969	0.082	0.214	0.544	0.013	0.035	0.088	0.096	0.249	0.631
1970	0.036	0.098	0.255	0.027	0.074	0.193	0.063	0.173	0.447
1971	0.058	0.160	0.416	0.025	0.070	0.181	0.084	0.230	0.597
1972	0.138	0.367	0.940	0.000	0.001	0.002	0.138	0.368	0.942
1973	-0.006	-0.018	-0.047	0.020	0.057	0.148	0.014	0.039	0.101
1974	0.073	0.220	0.585	0.002	0.007	0.018	0.075	0.226	0.604
1975	-0.014	-0.056	-0.161	0.014	0.055	0.157	0.000	-0.001	-0.004
1976	0.068	0.233	0.647	0.000	0.001	0.003	0.068	0.234	0.649
1977	0.097	0.283	0.749	0.009	0.025	0.066	0.105	0.308	0.815
1978	0.209	0.579	1.504	0.022	0.062	0.162	0.232	0.641	1.665
1979	0.183	0.501	1.298	0.016	0.045	0.115	0.199	0.546	1.413
1980	0.205	0.563	1.458	0.013	0.035	0.091	0.218	0.598	1.549
1981	0.274	0.713	1.812	0.013	0.035	0.088	0.287	0.748	1.900
1982	0.101	0.271	0.696	0.037	0.099	0.254	0.138	0.370	0.950
1983	0.345	0.899	2.283	-0.019	-0.050	-0.127	0.326	0.849	2.156
1984	0.434	1.103	2.773	0.036	0.092	0.232	0.471	1.195	3.005
1985	0.173	0.453	1.152	0.035	0.091	0.232	0.208	0.544	1.384

1986	0.079	0.214	0.552	0.040	0.108	0.278	0.119	0.322	0.830
1987	0.160	0.446	1.161	0.021	0.059	0.152	0.182	0.505	1.313
1988	0.028	0.082	0.216	0.066	0.193	0.511	0.094	0.275	0.727
1989	0.132	0.405	1.088	0.003	0.009	0.023	0.135	0.414	1.110
1990	-0.027	-0.105	-0.299	0.022	0.084	0.241	-0.005	-0.020	-0.058
1991	0.021	0.105	0.315	0.003	0.014	0.042	0.024	0.119	0.357
1992	0.111	0.478	1.396	0.009	0.037	0.108	0.120	0.515	1.504
1993	0.077	0.365	1.088	0.009	0.044	0.132	0.086	0.410	1.220
1994	0.065	0.312	0.929	0.010	0.049	0.146	0.075	0.361	1.075
1995	0.208	0.797	2.268	0.032	0.124	0.354	0.241	0.921	2.622
1996	0.186	0.750	2.161	0.018	0.071	0.204	0.203	0.821	2.364
1997	0.150	0.711	2.112	0.026	0.124	0.368	0.177	0.835	2.480
1998	0.089	0.675	2.141	0.014	0.105	0.332	0.103	0.780	2.473
1999	0.028	0.655	2.223	0.004	0.098	0.333	0.032	0.754	2.556

Notes:

1. Time series for equation (7) in the text, $g_{TFP} - g_{TFP,old} = ((\lambda_c / z_c - 1) z_c I_c - z_s I_s)/Y)(g_{I_c} - g_K)$.
2. Time series for $((\lambda_c / z_c - 1) z_c I_c - z_s I_s)/Y) g_K$.
3. Time series for $((\lambda_c / z_c - 1) z_c I_c - z_s I_s)/Y) g_{I_c}$.

$z_c I_c$: current dollar private fixed investments in computers, BEA.
$z_s I_s$: current dollar private fixed investments in software, BEA.
I_c, g_{I_c} : private fixed real investments in computers, chained 1996 dollars, BEA.
Y: current dollar domestic income, Jorgenson(2001).
g_K : growth rate of real capital services, Jorgenson(2001).

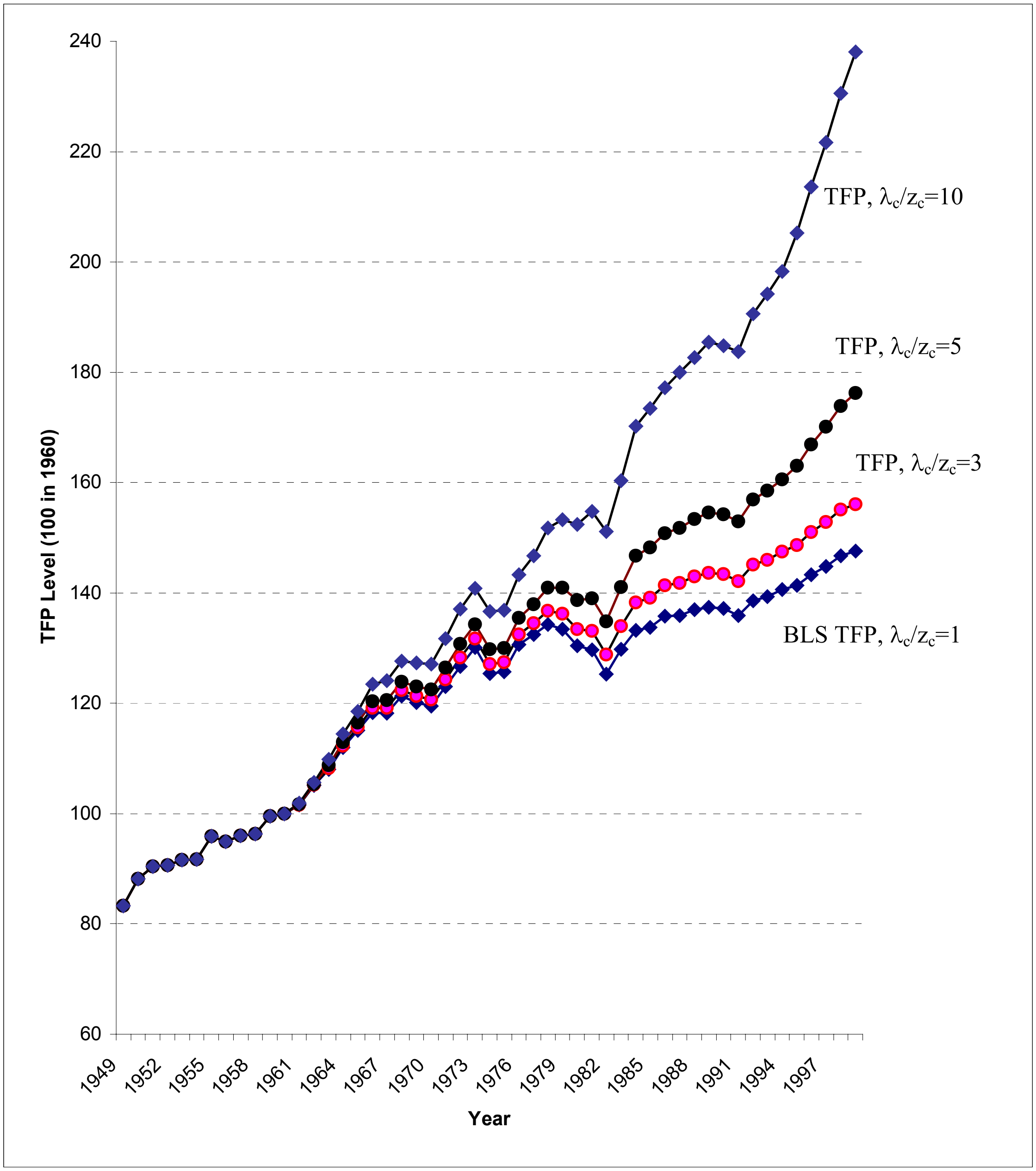
Table B: An Example of Growth Accounting Revision[1]

	1995 amount	1996 amount	Growth (from 1995-1996) amount change	Growth (from 1995-1996) percentage of GDP
Conventional Accounting				
Measured output	8,057.01	8,339.00	281.99	3.38%
Labor Services	4,770.70	4,861.70	91.00	
Capital Services	3,370.24	3,477.30	107.06	
TFP, growth contribution			83.93	1.01%
Intangible Investments[2]	120.06	188.5	68.44	0.82%
Amount of intangible investment needed to keep pace with growth in ordinary capital[3]		125.95	5.89	0.07%
Excess growth in intangible investments = Additional TFP growth			62.55	0.75%
Measured TFP growth			83.93	1.01%
Revised TFP growth			146.48	1.76%

Note:

1. Calculations are based on table A and Jorgenson (2001).
2. Assuming investments in computer related intangible assets are four times greater than the computer investments (i.e. $\lambda_c/z_c = 5$), and grow at the same rate of computer investments. $\lambda_c/z_c = 5$ implies that in 1996 these intangibles consist of $1.34 of software and $2.64 of other computer related intangibles for every dollar of computer investment.
3. If intangible investments grow at the same rate with measured capital services, there is no effect in TFP. See equation (6) and (7).

Figure A. TFP Level Index (1996 TFP level =100)



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