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GROWTH ACCOUNTING WHEN TECHNICAL CHANGE IS EMBODIED IN CAPITAL

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ABSTRACT

Many technological innovations are introduced through improvements in the design of new investment goods, thus raising the possibility that capital-embodied technical change may be a significant source of total factor productivity growth. There are, however, no systematic estimates of the size of the embodiment effect. This paper attempts to fill this gap by merging the estimates of quality change obtained from the price literature on quality change with a version of the conventional sources of growth model which allows for both embodied and disembodied technical change. This resulting estimates suggest that as much as 20 percent of the total factor productivity in growth U.S. manufacturing industry over the period 1949-83 is due to the embodiment effect. It is also found that for the equipment used in U.S. manufacturing, best practice technology may be as much as 23 percent above the average level of technical efficiency.

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GROWTH ACCOUNTING WHEN TECHNICAL CHANGE IS EMBODIED INCAPITAL

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Since the formulation of the model of vintage production in the late 1950s, economists have debated whether technical progress is due primarily to improvements in the design of new capital ("embodiment") or whether it is mainly "disembodied" and thus independent of the rate of capital formation.[1] In an early and influential paper, Edward F. Denison (1964) argued that the embodiment hypothesis was largely "unimportant" because changes in the age distribution of the capital stock have only a small impact on output growth, even if all technical change is capital embodied. This view was generally supported by the theoretical work on the subject (Edmund S. Phelps (1962), with important qualifications by R.C.O. Matthews (1964)), and by empirical tests of the vintage model (e.g. R.G. Gregory and Denis W. James (1973)).[2] And, more recently, Martin Neil Baily and Robert J. Gordon (1988) have argued that embodied technical change cannot be adduced as an explanation of the productivity slowdown of the 1970s.

The literature on quality change, on the other hand, implicitly assigns a significant role to embodied technical change as a determinant of the price of investment goods.[3] The study by Rossane Cole et. al. (1986) presents evidence for a huge quality component in the price of computers - between 10 and 20 percent <u>per year</u> - and this has led the Bureau of Economic Analysis (BEA) to revise their treatment of computers in the National Income and Product Accounts. And, while the magnitudes are less dramatic, the recent study by Robert J. Gordon (1990) reports a substantial quality component in a wide range of producers' durable equipment prices.

While these price-based studies of quality change suggest that technological improvements in the design of investment goods - embodied technical change - may be a significant source of total factor productivity change, they do not indicate just how important the embodiment effect actually is. This paper attempts to fill this gap by merging the estimates of quality change obtained from the price literature with a version of the conventional sources of growth model which allows for <u>both</u> embodied and disembodied technical change. This model, which is an extension of the models developed by Richard R. Nelson (1964) and Dale W. Jorgenson (1966), is applied to Bureau of Labor Statistics (BLS) data on output and inputs in U.S. manufacturing industries, combined with estimates of quality change derived from Gordon (1990). This procedure results in finding that as much as 20 percent (and perhaps more) of the BLS total factor productivity change can be directly associated with embodiment. In any event, these results suggest that embodied technical change played a nontrivial role in the growth of U.S. manufacturing industry over the period 1949-83.

One important consequence of the embodiment hypothesis is that new capital is more productive than older capital. Estimates presented in this paper imply that, for equipment used in U.S. manufacturing, best practice technology may be as much as 23 percent above the average level of technical efficiency. This, in turn, suggests the possibility of gains from shortening the average life of capital. However, confirming Denison (1964), the impact of the quality change associated with an increased rate of capital formation is found to be quite small: a one percentage point increase in the growth rate of producers' durable equipment leads to an immediate 0.127 percentage point increase in real output growth (other things equal), with a direct effect of 0.103 percent points and an indirect embodiment effect of 0.024 points. This finding provides little encouragement to those who want to justify tax incentives for capital on the basis of the embodiment hypothesis.

I. Alternative Models of Economic Growth

A. The Two Views of Capital

The two views of technical change differ markedly in their treatment of capital. Models of disembodied technical change are based on a concept of capital in which investment goods of different generations (or "vintages") differ only by some fixed factor associated with wear, tear and retirement. Assuming that the loss of productive efficiency due to such wear and tear proceeds at a constant rate δ, the amount of capital available at any point in time is thus the weighted sum of the surviving vintages:[4]

$$(1) \qquad K(t) = I(t) + (1-\delta)\, I(t-1) + \ldots + (1-\delta)^t I(0).$$

Vintage investment I(t) is, in principle, measured in some unit like number of machines. However, the δ weights convert each vintage of investment into new machine equivalents, so that one unit of five year old capital is equivalent in production to $(1-\delta)^5$ units of new capital. The stock K(t) can thus be interpreted as the number of new machine equivalents implied by the stream of past investment.

In contrast, the "new view" of capital assumes that successive vintages of investment also embody differences in technical design. This assumption captures the intuitive notion that technical progress in say, computers, is linked to improvements in the design of new machines, and that a computer of vintage 1990 will tend to be more efficient at producing output, *ceteris paribus*, than a machine of vintage 1980, even if there is no physical loss of capacity. In this view, capital stock computed as per (1) - i.e. under the assumption that design improvements can be ignored - will tend to understate the true productivity of the capital stock.

It is, however, possible to derive a version of (1) which does capture embodied improvements in design. Franklin Fisher (1965) shows that when a difference in technical design can be expressed as an equivalent difference in the *amount* of the investment good, an aggregate capital stock can be computed by defining vintage investment in terms of efficiency units.[5] That is, when "better" is equivalent to "more", investment can be measured in technical efficiency units H(t) which are equivalent to the amount of the investment good measured in natural units, I(t), times an index of technical efficiency,

$\Phi(t)$:

$$(2) \qquad H(t) = \Phi(t)I(t),$$

The index $\Phi(t)$ can be interpreted as the best practice level of technology in year t, and the change in $\Phi(t)$ as the quality differential between successive vintages. Similarly, the rate of change of $\Phi(t)$ is associated with the rate of embodied technical change.

Under the Fisherian "better" is "more" condition, the total amount of capital at time t measured in efficiency units can be written as

$$(3) \qquad J(t) = H(t) + (1-\delta)H(t-1) + \ldots + (1-\delta)^t H(0).$$
$$= \Phi(t)I(t) + \Phi(t-1)(1-\delta)I(t-1) + \ldots + \Phi(0)(1-\delta)I(0).$$

This is Solow's "jelly" capital, and the divergence between the two measures of capital K(t) and J(t) is summarized by the *average embodied technical efficiency*, $\Psi(t)$, defined as the weighted average of the best practice efficiency levels associated with each past vintage of investment,

$$(4) \quad \Psi(t) = \frac{I(t)}{K(t)}\Phi(t) + \frac{(1-\delta)I(t-1)}{K(t)}\Phi(t-1) + \frac{(1-\delta)^2 I(t-2)}{K(t)}\Phi(t-2) + \ldots .$$

This definition captures the intuitive notion that the average productivity of a collection of investment goods depends both on the relative efficiency of each vintage and on the relative amount of surviving (unadjusted) investment in each vintage. It also leads directly to the following relationships:

$$\text{(5a)} \quad \Phi(t) = \frac{H(t)}{I(t)} \qquad \text{(5b)} \quad \Psi(t) = \frac{J(t)}{K(t)}.$$

Equation (5a) is a restatement of (2), and equation (5b) follows directly from the definitions of $\Psi(t)$ and $J(t)$.[6]

The parameters $\Phi(t)$ and $\Psi(t)$ are also related to the price ratios associated with the quantities on the right hand side of equations (5a) and (5b). This relation follows from the observation by Jorgenson (1966) that the total amount spent on investment goods is invariant to the units in which the goods are measured.[7] A similar argument holds for the total income accruing to capital, implying that

$$\text{(6)} \quad P_I(t)I(t) = P_H(t)H(t) \quad \text{and} \quad P_K(t)K(t) = P_J(t)J(t),$$

where $P_I(t)$ denotes the price of new investment goods measured in units of $I(t)$ and $P_K(t)$ is the associated cost of using one unit of $K(t)$ for one time period; $P_H(t)$ and $P_J(t)$ are the corresponding price concepts for efficiency adjusted investment and capital. This invariance property leads immediately to a set of equations which are inversely symmetric to (5a) and (5b):

$$\text{(5c)} \quad \Phi(t) = \frac{P_I(t)}{P_H(t)} \qquad \text{(5d)} \quad \Psi(t) = \frac{P_K(t)}{P_J(t)}.$$

These price equations allow us to measure the unobserved embodiment parameters

$\Phi(t)$ and $\Psi(t)$ using estimates of the relative price ratios. Thus, whenever the unobserved parameters $\Phi(t)$ and $\Psi(t)$, or their growth rates, appear in the modified sources of growth equations developed in the following sections, the corresponding (observable) relative prices can be inserted in their place to obtain an estimate of the relative importance of disembodied and embodied technical change.[8]

B. The Aggregate Production Function

As originally formulated by Solow (1960), the process of embodied technical change is an autonomous process: the increased efficiency of new capital goods is seen as increasing the quantity of capital input measured in efficiency units, but no resources are expended to achieve this increase. As a result, the output of investment goods, which are subsequently added to the quality-adjusted capital stock, is not adjusted for quality improvement. In contrast, the variant of the embodiment model developed by Evsey D. Domar (1963) and Jorgenson (1966) adjusts both investment output and capital input for improvements in technical quality, i.e. measures both in efficiency units. Assuming the appropriate degree of separability, the aggregate production function associated with the Domar-Jorgenson variant of the embodiment model can be written as

$$(7) \qquad O(t) = C(t) + \Phi(t)I(t) = F(L(t),\Psi(t)K(t),t) \ ,$$

whereas the version of the model analyzed by Solow (1960), Nelson (1964), and

Fisher (1965) assumes that $\Phi(t)=1$ on the left hand side of (7).[9] As noted below, the appropriateness of this assumption is the subject of active debate.

The growth equation associated with (7) is derived under the competitive equilibrium assumption that prices are proportional to marginal products and that production takes place under constant returns to scale. Differentiation of the function (7) and substitution of prices for marginal products gives an equation which relates the growth rate of output, defined as the shared-weighted sum of consumption and investment, to the share-weighted growth rates of labor and capital (measured in conventional units) and the growth rates of the two types of technical change:[10]

$$(8) \qquad \begin{aligned} \hat{O}(t) &= (1-\sigma(t))\,\hat{C}(t) + \sigma(t)\,\hat{I}(t) + \sigma(t)\,\phi(t) \\ &= (1-\pi(t))\,\hat{L}(t) + \pi(t)\,\hat{K}(t) + \pi(t)\,\psi(t) + \lambda(t). \end{aligned}$$

Hats over variables denote rates of growth of output and input; $\phi(t)$ is the growth rate of $\Phi(t)$ and the term $\sigma(t)\phi(t)$ measures the extent of the induced quality change in investment; $\psi(t)$ is the growth rate of $\Psi(t)$ and $\pi(t)\psi(t)$ measures quality change on the input side (when this term is positive and $\sigma(t)\phi(t)$ is zero, embodied technical change is of the Solow-Nelson-Fisher form); finally, $\lambda(t)$ is the rate of disembodied technical change (defined as the shift in the function F). The investment and capital income shares, which are to

$$(9) \qquad \sigma(t) = \frac{P_H(t)H(t)}{V(t)} = \frac{P_I(t)I(t)}{V(t)}, \quad \pi(t) = \frac{P_J(t)J(t)}{V(t)} = \frac{P_K(t)K(t)}{V(t)},$$

embody the invariance property of (6). $V(t)$ is the value of input and output, $P_L(t)L(t) + P_J(t)J(t) = P_C(t)C(t) + P_H(t)H(t)$.

C. The Importance of Embodiment

The growth equation (8) shows that embodiment influences output growth in two ways. An increase in $\phi(t)$ will lead directly to an increase in the growth rate of quality-adjusted investment, $\hat{H}(t)$, and this, in turn, increases the growth rate of quality-adjusted output, $\hat{O}(t)$. On the input side, an increase in $\phi(t)$ raises the productivity of new capital and thus leads to future increases in $\Psi(t)$. The relative importance of this effect on the input side can be measured by the size of $\pi(t)\psi(t)$ relative to the total "amount" of technical change, $\pi(t)\psi(t) + \lambda(t)$. If technical change is entirely of the embodied form, $\lambda(t)=0$, and all technical change is due to the $\pi(t)\psi(t)$ effect.

Any comparison of the relative importance of $\psi(t)$ and $\lambda(t)$ must recognize that $\psi(t)$ is not a fully exogenous parameter like $\lambda(t)$, but depends instead on the rate of capital formation. This point is underscored by the fact that our basic growth equation (8) can also be written entirely in terms of quality-adjusted variables, i.e. as

$$\text{(8a)} \qquad \hat{O}(t) = (1-\sigma(t))\,\hat{C}(t) + \sigma(t)\,\hat{H}(t) = (1-\pi(t))\,\hat{L}(t) + \pi(t)\,\hat{J}(t) + \lambda(t),$$

The variable $\psi(t)$ does not appear in this form of the growth equation, since all embodiment effects are suppressed into the quality-adjusted variables. The choice between the $J(t)$ and $\Psi(t)K(t)$ specifications is thus a matter of taxonomy and not of fundamental technological differences.

This point can be made in another way. Instead of expressing (8) entirely in terms of quality-adjusted variables, we can write this equation entirely in terms of the unadjusted variables $\hat{Q}(t)$, $\hat{I}(t)$, and $\hat{K}(t)$. In this case, (8) becomes:

$$
\begin{aligned}
\text{(8b)}\quad \hat{Q}(t) &= (1-\sigma(t))\,\hat{C}(t) + \sigma(t)\,\hat{I}(t) \\
&= (1-\pi(t))\,\hat{L}(t) + \pi(t)\,\hat{K}(t) + \pi(t)\psi(t) - \sigma(t)\phi(t) + \lambda(t).
\end{aligned}
$$

The term $\sigma(t)\phi(t)$ now appears on the right hand side of the growth equation in order to correct for the mismeasurement of output. When $Q(t)$ is used instead of $O(t)$ and the latter is the correct measure of output, $\hat{Q}(t)$ understates the true growth rate of real output by the amount $\sigma(t)\phi(t)$.

Equation (8b) is familiar to students of economic growth as a variant of the Solow (1957) model of the "residual," which can be written as

$$
\text{(10)}\qquad \hat{Q}(t) = (1-\pi(t))\,\hat{L}(t) + \pi(t)\,\hat{K}(t) + \hat{T}(t).
$$

In this form, the growth rate of real output is the share-weighted sum of the growth rates of the inputs plus the growth rate of "total factor productivity," $\hat{T}(t)$. This variable is also termed "output per unit input," the "residual," or "the measure of our ignorance," since $\hat{T}(t)$ is measured as the residual growth rate of output not attributable to the inputs of capital and labor.

A vast empirical literature is based on this equation, almost all of which regards $\hat{T}(t)$ an a estimate of disembodied improvements in productivity.[11] However, it is readily apparent that the total factor productivity residual is equal to

$$(11) \quad \hat{T}(t) = \pi(t)\,\psi(t) - \sigma(t)\phi(t) + \lambda(t)$$

when technical change is both embodied and disembodied and economic growth proceeds according to (8b). This result shows that the total factor productivity residual is composed of terms associated with both types of technical change, except in the singular case of Golden Rule steady state growth. In this case, Jorgenson (1966) shows that since $\pi(t)=\sigma(t)$ and $\psi(t)=\phi(t)$, the mismeasurement of embodiment on the output side just cancels the embodiment effects on the inputs side, leaving $\hat{T}(t) = \lambda(t)$.

These results have important implications for the debate over whether investment good deflators should be adjusted for quality change. In a recent book, Denison (1989) argues that this adjustment is inadvisable because it would assign to capital formation an effect that is more appropriately viewed as an advancement in knowledge. In this view, I(t) and not H(t) is the appropriate measure of investment, K(t) and not J(t), is the proper measure of capital, and (10), not (8a), is the appropriate growth equation. However, it is clear from (11) that if technical change happens to be both embodied <u>and</u> disembodied, the failure to adjust investment, both as an output and an input, for quality change - i.e. to proceed as though (10) were correct - merely suppresses the embodiment terms into the total factor productivity residual.

D. The Elasticity of Embodiment

The preceding analysis represents the growth equation associated with the technology (7) in three separate, but equivalent, ways. There is yet another way of representing this equation by using a parameter associated with the "wedge" between the best practice level of technology at time t, $\Phi(t)$, and the average level in the preceding year, $\Psi(t-1)$, defined as

$$(12) \qquad \varepsilon(t) = \frac{\Phi(t)-\Psi(t-1)}{\Psi(t-1)} .$$

This "elasticity of embodiment" is of interest in its own right, since it measures the efficiency disadvantage experienced by an average piece of capital relative to new capital. When efficiency decay proceeds at a constant rate δ, it can be shown that the growth rate of average embodied efficiency is equal to

$$(13) \qquad \psi(t) = \varepsilon(t) \frac{I(t)}{K(t-1)} = \varepsilon(t) \hat{K}(t) + \varepsilon(t)\delta.$$

The first equality indicates that the growth rate of average embodied efficiency depends on two factors: the percentage distance between average and best practice efficiency and the rate of <u>gross</u> investment. Even if the rate of embodied technical change falls to zero in one year, the average efficiency will grow if best practice is above the average level of efficiency and gross investment takes place. On the other hand, if gross investment is zero, then average efficiency will remain constant regardless of the underlying rate of embodied technical change.

The second equality indicates that $\varepsilon(t)$ can be regarded as the elasticity of the average level of efficiency, $\Psi(t)$, with respect to unadjusted capital. This implies that an increase in unadjusted capital input feeds back into the average level of efficiency. However, it is also the case that the average level may increase even if there is no net capital formation, because replacement investment brings in new, and therefore best-practice, capital.

Our basic growth equation can be rewritten, in light of (13), to capture the feed-back effect of unadjusted capital on output growth. Together, (8b) and (13) imply

$$(8c)\quad \hat{Q}(t) = (1-\pi(t))\,\hat{L}(t) + \pi(t)(1+\varepsilon(t))\,\hat{K}(t) + \pi(t)\varepsilon(t)\delta - \sigma(t)\phi(t) + \lambda(t)$$

This form of the growth equation indicates that when capital is not adjusted for quality change, the correct output elasticity of capital is $\pi(t)(1+\varepsilon(t))$, and not the usual $\pi(t)$, which is now the elasticity of output with respect to adjusted capital, $J(t)$. This, in turn, suggests, that were BEA to abandon its adjustment of computer prices for quality change, the failure to make the quality adjustment when embodied technical change is in fact occurring would lead to an unexpected wedge between the output-elasticity and the cost share of capital. As before, when embodied technical change is ignored, it pops up again elsewhere in the analysis.

The feed-back effect associated with unadjusted capital suggests that capital formation has a double impact on output growth. However, the feed-back effect must be recognized as transitory. This effect operates through a reduction in the average age of capital stock: as the growth rate of unadjusted capital increases, the stock becomes younger and the average efficiency increases. This process reaches a logical limit when all capital is new, implying that that $\Phi(t)=\Psi(t)$ and that the growth rate of the average efficiency equals the growth rate of embodied technical change. It therefore follows that the $\epsilon(t)\pi(t)$ feedback is at best a transitory effect which raises the level of output but does not permanently change its rate of growth.[12]

II. Comparing the Alternative Views of Technical Change

A. BLS Total Factor Productivity Estimates

Equation (10) forms the conceptual basis for the large sources of growth literature, including the official estimates of total factor productivity developed by the Bureau of Labor Statistics (1983) for the private business sector of the U.S. economy. The BLS has recently extended this program to include major industries within the manufacturing sector and, in the process, has shifted the definition of real output from a value added concept to a gross output concept and expanded the list of factor inputs to include energy, materials, and purchased services (in addition to capital and labor).

The results of this "KLEMS" segment of the BLS program are reported in William Gullickson and Michael J. Harper (1987), and are shown in Table 1.[13] The BLS data indicate that real output grew at an average annual rate of 3.13

Table 1 - Sources of Growth in U.S. Manufacturing
Conventional Model
(Average Annual Share Weighted Growth Rates)

	1949-83	1949-73	1974-83
Output	3.13	4.04	0.95
Capital	0.72	0.77	0.60
Labor	0.33	0.63	-0.40
Energy	0.06	0.10	-0.04
Materials	0.59	0.69	0.34
Services	0.37	0.36	0.39
TFP	1.06	1.48	0.06

Source: Computed from Bureau of Labor Statistics data, described in Gullickson and Harper, using Tornqvist approximation to equation (10).

percent over the period 1949-83, and that TFP was the largest contributor, accounting for slightly more than one-third of output growth. Intermediate inputs (energy, materials, and services) account for another third of the remaining growth, with capital accounting for almost 25 percent and labor, the smallest contributor, accounting for approximately 10 percent of output growth.

Table 1 also reveals that growth was much larger during the first part of the sample period (4.04 percent for the period 1949-73) than during the second part (0.95 percent). The drop-off after 1973 is the highly publicized "productivity slowdown" which affected virtually all sectors and regions of the U.S. economy, as well as much of the developed world. The results of Table 1 indicate that total factor productivity accounted for 46 percent of the slowdown in output, with the decrease in the contribution of labor accounting for one-third, and capital, energy, materials, and services explaining only a small fraction (a combined 20 percent) of the reduction in output growth.

B. Price-Based Estimates of Embodied Technical Change

The KLEMS data set has the additional feature that capital input is disaggregated into four general types of tangible capital - equipment, structures, land, and inventories - and equipment is further divided into the seventeen categories listed in Appendix Table A1 (based on the BEA classification system). It is apparent from the first column of this table that three types of equipment - metalworking, general industrial, and special industrial - account for over 60 percent of the rental income accruing to equipment used in manufacturing, while office and computing equipment account for a relatively small (but growing) share. This is significant because of the attention paid to quality change in computing equipment.

The asset detail provided by the BLS data is essentially the same as the asset classification used in a major new study of quality-adjusted equipment price indexes by Gordon (1990).[14] Gordon's quality-adjusted indexes correspond, conceptually, to our $P_H(t)$, and if we assume that the BEA investment price indexes used by BLS correspond to the unadjusted $P_I(t)$, an estimate of $\Phi(t)$ follows immediately from equation (5c) as the ratio of BLS and Gordon price estimates. This provides an independent source of information about $\Phi(t)$ which is of obvious value to the task of sorting out the relative contribution of the various components of the total factor productivity residual (11), but two caveats must be kept in mind.

First, the investment price indexes used by BLS already embody some degree of quality adjustment. The magnitude of this prior adjustment is not known, and for equipment classes other than office and computing machinery (OCAM), Griliches (1983) suggests that it could be relatively small. The BLS price index for the OCAM class does, however, reflect the BEA decision to adjust computers for quality change. While this class receives a relatively small weight in average $\Phi(t)$ for all manufacturing equipment (the relative weight assigned to the OCAM class - i.e. the share of total income accruing to equipment - is only 8 percent over the period 1949-83), it does introduce a downward bias in our aggregate estimate of embodied technical change.[15]

On the other hand, some part of the quality differentials captured by the ratio of BLS and adjusted price indexes may not be due to embodied technical change at all, but instead reflect other factors like a producer's decision to increase or decrease product quality in the face of a change in the demand for "quality." Such a decision may be accomplished by selecting from an existing set of product qualities rather than by developing new technology. Moreover, there simply may be a lag in making investments which embody the new technology (a standard result in the vintage production literature is that profit maximizing producers will keep obsolete equipment as long as it generates a positive quasi-rent or the remaining present value of these quasi-rents exceeds scrap value). Thus, our procedure of interpreting the Gordon quality-adjusted indexes $P_H(t)$ as though they reflected only embodied technical change, and assuming that the BLS $P_I(t)$ are commensurate with the

Table 2 - Parameters of Embodied Technical Change
Producers' Durable Equipment Used in Manufacturing Industry 1/

	1949-83	1949-73	1974-83
Embodied Technical Change, $\phi(t)$ 2/	3.44	3.43	3.47
Average Embodied Efficiency, $\psi(t)$ 2/	3.00	2.91	3.20
Elasticity of Embodiment, $\varepsilon(t)$ 3/	0.23	0.23	0.22

1/ Source: see Appendix Table A1.
2/ Average Annual Arithmetic Growth Rates (in percentage points)
3/ Elasticity based on equation (12) of the text.

estimated $P_H(t)$ in every regard except that they exclude embodied technical change, undoubtedly introduces a bias in our estimate of the level of $\Phi(t)$. Whether or not there is a corresponding bias in the growth rate of $\Phi(t)$ is less clear, since a constant proportionate bias in the level would not carry over to the growth rate (although it does seem likely that the OCAM problem leads to net downward bias in the growth rate of the true $\Phi(t)$).

The growth rates of the $\Phi(t)$ derived from the estimates of $P_H(t)$ and $P_I(t)$ are summarized in Table 2 for the three time periods displayed in Table 1. The share-weighted average annual growth rate of embodied technical change, $\phi(t)$, is found to be 3.44 percent for the period 1949-1983, and to be virtually identical in the 1949-73 and 1974-83 sub periods. Appendix Table A1, which provides corresponding results for the seventeen components of Producers' Durable Equipment (PDE) used in U.S. manufacturing industries, shows that quality change is significant for all categories of PDE, with average annual growth rates ranging from 1.24 to 11.39 percent. Computers exhibit the largest adjustment, despite the quality correction already built into the BLS price series, but in view of the relatively small cost-share associated with computers, and the significant rates of quality change associated with the larger equipment classes (metal working machinery and general and special industry equipment), it is not appropriate to conclude that quality change in the OCAM class determines the overall estimate of $\phi(t)$.

Estimates of the growth rate of average embodied technical efficiency, $\psi(t)$, are also reported in Table 2. Since the estimates of $\Psi(t)$ are related to the $\Phi(t)$ via equation (4), as thus $\psi(t)$ is related to the marginal rate of embodied technical change (the $\phi(t)$'s), it is not surprising that the growth rate of the average efficiency is also large. The share-weighted average $\psi(t)$ grew at an average annual rate of 3.00, which is somewhat smaller than the growth rate of the aggregate $\phi(t)$, but the magnitude of these two variables implies a substantial quality-adjustment for both investment output and equipment input. As with the $\phi(t)$'s, the $\psi(t)$'s are very similar in the 1949-73 and 1974-83 sub periods. The Appendix Table A1 gives the corresponding estimates of $\psi(t)$ for each subcategory of PDE.

Average values of $c(t)$ are shown in the last column of Table 2, for the different time periods, and the share-weighted average across categories is found to be 0.23. Subject to the caveats noted above, this implies that the best practice technology was 23 percent above the average level, which, in turn, suggests that many older manufacturing plants in the U.S. may be operating at a significantly lower level of embodied technical efficiency than recently constructed plants.

This is one of the main empirical results of this paper and it suggests that there is a potentially large gain to be gotten from shortening the age structure of capital. However, the estimated impact on output growth turns out to be small. Multiplication by equipment's cost share yields a value of $\pi_e(t)c(t)$ of 0.024. This is approximately the cost advantage enjoyed by a firm which operates entirely new machines relative to a firm whose equipment has the average level of technical efficiency. A proportionate increase in all categories of PDE which increases $\hat{K}(t)$ by one percent would then increase the growth rate of output by 0.127 percent, *ceteris paribus*. The fact that such a large increase in the growth of equipment should lead to such a small effect confirms the findings of Denison (1964) that changes in the age structure of capital have little effect on output growth.

C. The Quality-Adjusted Sources of Growth

The introduction of quality adjustments into the analysis of growth affects both capital input and capital output. We have considered the quality-adjustment of capital input in the preceding section and now turn to the quality adjustment of output. Recalling equation (8c), this involves an adjustment of conventionally measured output by $\sigma(t)\phi(t)$. We have already described the procedure for estimating $\phi(t)$, and now turn to the problem of estimating $\sigma(t)$, the share of investment goods in U.S. manufacturing output.

In principle, all resource-using improvements in the quality of output should be included in the estimate of $\sigma(t)$, since there is no *a priori* reason to restrict the estimation to the quality adjustment to producers' durable

Table 3 - Comparison of Adjusted and Unadjusted Growth Rates (Average Annual Growth Rates and shares)

	1949-83	1949-73	1974-83
Equipment Growth Rate:			
Unadjusted BLS ($\hat{K}$)	4.37	3.84	5.66
Quality Adjusted (J)	7.28	6.66	8.76
Output Growth Rate:			
Unadjusted BLS ($\hat{Q}$)	3.13	4.04	0.95
Quality Adjusted (O)	3.53	4.43	1.37
Equipment's Share of:			
Cost (π_e)	0.103	0.108	0.090
Output (σ)	0.130	0.130	0.130

Source: Author's calculations described in text.

Table 4 - Alternative Sources of Growth with Embodied Technical Change (Share Weighted Average Annual Growth Rates)

	1949-83	1949-73	1974-83
Output ($\hat{O}$)	3.53	4.43	1.37
Capital ($\hat{K}$)	0.72	0.77	0.60
Labor ($\hat{L}$)	0.33	0.63	-0.40
Energy ($\hat{E}$)	0.06	0.10	-0.04
Materials ($\hat{M}$)	0.59	0.69	0.34
Services ($\hat{S}$)	0.37	0.36	0.39
Emb. T.C. (ψ)	0.30	0.31	0.28
Residual (λ)	1.17	1.57	0.20

Source: Computed from Tornqvist approximation to equation (8).

equipment. However, we only have data from Gordon on PDE, so our analysis is limited to these categories of capital. Moreover, the BLS data which underlie this study do not include an allocation of manufacturing output between final and intermediate demand, nor of final demand among various categories of consumption, investment, etc. As a result, it was necessary to go outside the BLS data set and use input-output data to obtain an estimate of $\sigma = 0.1304$.[16]

Estimates of the quality-adjusted growth rate of output are shown in Table 3. For the period as a whole, the adjustment adds about 0.40 percentage points to output growth, a fairly significant increase when compound growth rates are involved. The alternative sources of growth classification implied by equation (8) is presented in Table 4. Because $\hat{O}(t)$ is used as the measure of real output the term $\sigma(t)\phi(t)$ is omitted. $\lambda(t)$ is measured as the residual output not explained by other factors.

It is apparent that the last two terms of Table 4 are the most important sources of quality-adjusted growth. Together, they explain 42 percent of the growth rate of quality-adjusted output, compared to 34 percent in the BLS classification of Table 1. Unadjusted capital growth explains 20 percent of $\hat{O}(t)$ compared to 23 percent in Table 1, but if one adds the embodiment term, $\pi_e(t)\psi(t)$, to the growth rate of unadjusted capital, $\hat{K}(t)$, to obtain $\hat{J}(t)$, the total capital effect is 29 percent. The relative contribution of each factor to the productivity slowdown is roughly the same in Table 4 as in the conventional view of Table 1.

Table 4 also provides an insight into the relative importance of quality change in investment goods as a source of output growth. According to Table 4, quality change accounted for approximately 20 percent of the residual

Table 5 - Reconciliation of Conventional TFP
with Embodiment Variables

		1949-83	1949-73	1974-83
TFP,	Tbl. 1	1.06	1.48	0.06
$\pi\psi$,	Tbl. 4	0.30	0.31	0.28
$-\sigma\phi$,	Tbl. 3	-0.40	-0.40	-0.42
λ,	Tbl. 4	1.17	1.57	0.20

Source: Based on Tornqvist approximation to equation (11).

output growth not attributed to inputs. If this quality change is associated with embodied technical change, we are led to conclude that, for the period as a whole, technical change is <u>not</u> predominantly of the embodied form. Note in that this holds even though the growth rate $\psi(t)$ averages 3.0 percent per year, because this growth rate is weighted by equipment's share of total cost, $\pi_e(t)$, which is only 10.3 percent.

The picture is, however, different in individual sub periods. For the pre-slowdown era, $\lambda(t)$ accounts for 84 percent of the total, but for only 42 after the slowdown. It is thus tempting to attribute the slowdown to a reduction in the rate of disembodied technical change, but it is important to remember that the terminal year, 1983, is near the trough of a recession, and that because $\lambda(t)$ is measured as a residual, it embodies changes in capital utilization, measurement errors, and unidentified quality changes, as well as disembodied technical change.[17]

The terms $\pi_e(t)\psi(t)$ and $\lambda(t)$ in Table 5 are related to the total factor productivity residual via equation (11). To investigate the quantitative significance of this relationship, Table 5 provides a reconciliation between total factor productivity as calculated by BLS and the quality-adjusted terms of Table 4. Conventional TFP grew at a compound rate of 1.06 percent over the 1949-83 period, and this can be resolved into the following three components: $\pi_e(t)\psi(t)$, which accounts for 0.30 percentage points of the total TFP growth; $-\sigma(t)\phi(t)$, which provides an offset of -.40 points; and the residual $\lambda(t)$, which equals 1.17 points. This implies that the two quality effects were roughly offsetting and that $\lambda(t)$ and the TFP residual are roughly equal.

III. Summary and Conclusions

This paper has revisited the theory of the embodiment hypothesis and has recast and extended old results in a way that makes them more relevant to the contemporary debate about the adjustment of investment goods for quality change, and about the role of embodied technical change as a source of economic growth. As a by-product of this theoretical development, it is shown that the failure to adjust capital for quality change when such change is actually occurring has the effect of suppressing the quality effects into the conventional total factor productivity residual, thus enhancing this residual's reputation as "a measure of our ignorance." By extension, our results suggest that BEA is justified in adjusting computer prices for quality change and that BEA should extend this adjustment to all producers' durable equipment.

The theoretical framework is then used to merge the recently developed data sets from Gordon and the BLS. Subject to the various caveats about the price data (in particular, the possible under counting of the quality change already built into the BLS estimates), it was found that best practice technology exceeds the average level by around 23 percent, and that approximately 20 percent of the residual growth of quality-adjusted output could be attributed to embodied technical change. On the other hand, the increase in the average rate of embodied technical change due to an increase in the rate of capital formation was found to be small.

The introduction of BLS and Gordon investment price indexes into the growth accounting framework thus leads to the conclusion that changes in the quality of capital had a nontrivial impact on the growth of U.S. manufacturing industries from 1949 to 1983. These results also suggest that embodiment increases the short-run elasticity of output of (unadjusted) capital, but that Denison (1964) was apparently right about the unimportance of this increase on output growth. It should also be noted that these conclusions could change significantly if adjustments for quality change are extended to consumer goods and intermediate inputs.[18] If these goods experience a rate of quality improvement equal to that of investment goods, the quality-adjusted growth rate of real output in U.S. manufacturing would more than double and a revised Table 4 would show a huge contribution to productivity growth.

NOTES

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1. For the original contributions, see Leif Johansen (1959), W.E.G. Salter (1960), and Robert M. Solow (1960).

2. Gregory and James note that empirical tests of the vintage model using times series data have found that " ... vintage models were neither markedly superior nor inferior to non-vintage models (page 1133)" , and that cross-sectional studies produced mixed results. Studies using data for individual plants (e.g. the study of the electric power generation industry by Michael Gort and Raford Boddy (1967)) tended to find vintage effects, as did Michael D. Intriligator (1965), while studies using data for manufacturing industries did not (e.g. Zvi Griliches (1967)). Gregory and James themselves find little evidence for the embodiment hypothesis.

3. See Griliches (1961), Robert E. Hall (1968,1971), Rosen (1974), Jack E. Triplett (1983,1990), and Robert J. Gordon (1990).

4. The case in which depreciation is not geometric involves a more complicated arithmetic (see, for example, the recent survey by Charles R. Hulten (1990)), but the basic concept of capital as an efficiency weighted sum of past vintage investments remains the same.

5. Fisher (1965) shows that necessary and sufficient conditions for the existence of an aggregate stock of capital are given by the Leontief theorem, which states that the marginal rate of substitution between any pair of inputs within the aggregate must be independent of the inputs outside the aggregate. Under constant returns to scale, this condition requires that differences between vintage technologies must be expressible as

$$(4) \qquad f^{\nu}(L(t,\nu),I(\nu)) = f(L(t,\nu),\zeta(\nu)I(\nu)), \text{ for each } \nu \text{ at time } t.$$

This implies that the difference in technology from one vintage to the next, in each year t, must be expressible as the difference between the productivity, or quality, of capital of different vintages. Specifically, the difference in the relative productivity of vintage capital must be a constant which depends only on the vintage at each t.

6. As we shall see below (footnote (9)), the term $\Psi(t)$ is related to the Solow-neutral technical change parameter in an aggregate production function such as (7). And, as noted in footnote (12), $\Psi(t)$ is also related to the average age parameters of the Nelson (1964) model.

7. The price of any good is denominated in dollars per unit of the good. A change in the of units measurement will therefore change the price per unit, but leave the total value (price times quantity) unchanged. For example, when a firm spends $10,000 for a new computer, and this computer is twice as efficient as last year's model, we could equally say that the price per unit $10,000 and that one unit was purchased (measured in terms of this year's units), or that two units were purchased at $5,000 each.

8. There is an alternative interpretation of Jorgenson (1966) which stresses pure measurement errors. Equation (6) implies that any error made in estimating the true investment good price leads directly to an offsetting error in the estimated quantity. Thus, if $H(t)$ is the correct concept of investment, and it is estimated by deflating the value of investment spending using a biased estimate of the investment price $P_I(t)$, the result will be a proportionately biased quantity like $I(t)$. However, while this interpretation is certainly valid for measurement errors, it is still true that when embodied technical change introduces a systematic wedge between the price of investment goods measured with and without regard for quality improvement, (5c) and (5d) can be used to estimate this wedge given observation of <u>both</u> prices.

9. This specification is closely related to the model of factor augmentation technical change. In this model, the technology is written as $O(t) = F(\theta(t)L(t),\eta(t)K(t))$, with $\theta(t)$ and $\eta(t)$ defined as the augmentation parameters of labor and capital, respectively. The term $\eta(t)$ is almost identical to the $\Psi(t)$ of this paper, except that it is an efficiency parameter which depends only on time, while $\Psi(t)$ is a variable which depends on underlying efficiency parameters and on the age structure of the capital stock.

10. The growth rates of capital and labor in (7) are, in principle, the share-weighted growth rates of the individual elements of the vectors of capital and labor in (7). However, data limitations usually require that $K(t)$ and $L(t)$ are linear aggregates (for further discussion, see the survey by Hulten (1990)).

11. See Solow (1957), John Kendrick (1961), Denison (1962), and Jorgenson and Griliches (1967) for milestone studies in the empirical literature, and BLS (1983) and Jorgenson, Frank M. Gollop, and Barbara M. Fraumeni (1987) for more recent references. These studies all use some discrete-time variant of (10), but with significant differences in the definitions of the various arguments of (10). The methods used to transform the continuous-time formulation into a discrete-time equivalent also vary, but most recent studies - including this paper - have tended to use the Tornqvist (or translog) method. In this approach, the continuous growth rate of each variable is approximated by the the first difference in the natural log of that variable (e.g. $Q(t)$ becomes

$\ln Q(t) - \ln Q(t-1)$), and the continuous income shares are approximated by the arithmetic average of the current and preceding periods shares (e.g. $\pi(t)$ becomes $(1/2)[\pi(t)+\pi(t-1)]$).

12. The variant of the embodiment model developed by Nelson (1964) is particularly useful in illustrating the relationship between the rate of embodied technical change and of the average age of capital. Nelson shows that our condition (5b) can be approximated by the equation

$$\hat{J}(t) = \hat{K}(t) + \phi(t)(1 - \Delta\bar{a})$$

where $\bar{a}$ is the average age of the capital stock. The low limit on the age of the stock is attained when all capital is new, implying that $\Delta\bar{a}$ is zero thereafter and that the embodiment effect vanishes.

13. Due to subsequent revisions of the data, the estimates presented in this table differ slightly from those presented in Table 3 of Gullickson and Harper for the same period. Both papers use the same Tornqvist approximation to equation (10), and the reader is referred to the Gullickson and Harper paper and to BLS (1983), for a detailed description of the methods used in constructing the data set. Details of the procedures used in this paper will also be made available upon written request.

14. In his Appendix B, Gordon presents estimates quality adjusted price indexes for sixteen types of equipment and their components. This classification matches the BLS asset classification (which refers only to equipment used in manufacturing industries) for 11 types of asset, which account for almost 70 percent of the income accruing to equipment. Gordon's "alternative group average" index was used for these classes as an estimate of $P_H(t)$. Quality-adjusted indexes for the remaining six BLS classes were obtained from the Gordon's Appendix C of "Secondary PDE Categories."

15. For the period 1949-73, the BLS OCAM deflator rises at an average annual rate of 4 percent, and then <u>falls</u> at an annual rate of 5 percent over the period 1973-83. By comparison, the Gordon quality-adjusted OCAM estimates are, respectively, -7 percent and -12 percent for these periods, suggesting that the estimates of the OCAM $\Phi(t)$ derived from the ratio of BLS and Gordon price indexes *understates* embodied technical change for this class. It is worth noting, however, that the time path of the BLS OCAM price index is very different from the time paths of the other BLS equipment price indexes, which show an acceleration, not a deceleration, during the 1970s. While this does not establish whether or not these other prices indexes have been adjusted for quality change - the rates of quality change for these assets may be swamped by the high rate of general inflation - it is certainly consistent with the evidence reviewed by Griliches (1983) which suggests that the amount of quality-adjustment in these asset classes is relatively small.

16. These data were provided by my colleague, Clopper Almon. Unfortunately, annual estimates of σ were not available, so the results were averaged to yield the estimate used in this study.

17. While the Tornqvist-BLS methodology should, in principle, take changes in capital utilization into account (Ernst R. Berndt and Melvyn A. Fuss (1986)), the TFP residual is, in practice, highly pro-cyclical. As a result, some portion of the divergence between the change in the stock of capital and the change in the corresponding flow of capital services is probably suppressed into the TFP residual.

18. Labor input might also be added to this list and, in this regard, it is interesting to note that the Jorgenson-Griliches (1967) labor quality index is similar to the average embodied efficiency index $\Psi(t)$ of this paper. The Jorgenson-Griliches labor quality index is the ratio of the Divisia index of labor input (inclusive of quality differentials) to the total number of hours worked (exclusive of quality differences). The BLS data on labor input used in our calculations is based on total hours worked and thus excludes the quality component.

REFERENCES

Baily, Martin Neil and Gordon, Robert J.,"Measurement Issues, the Productivity Slowdown, and the Explosion of Computer Power," Brookings Papers on Economic Activity, 2:1988, 347-420.

Berndt, Ernst R. and Fuss, Melvyn A., "Productivity Measurement With Adjustments for Variations in Capacity Utilization, and Other Forms of Temporary Equilibrium," Journal of Econometrics, 1986, 33, 7-29.

Cole, Rosanne, Chen, Y.C., Barquin-Stolleman, J.A., Dullberger, E., Helvacian, N., and Hodge, J.H., "Quality-Adjusted Price Indexes for Computer Processors and Selected Peripheral Equipment," Survey of Current Business, January 1986, 66, 41-50.

Denison, Edward F., The Sources of Economic Growth in the United States and the Alternatives Before Us, New York: Committee for Economic Development,1962.

________, "The Unimportance of the Embodiment Question," American Economic Review, March 1964, 54, 90-94.

________, Estimates of Productivity Change by Industry: An Evaluation and an Alternative, Washington, D.C.: The Brookings Institution, 1989.

Domar, Evsey D., "Total Factor Productivity and the Quality of Capital," Journal of Political Economy, December 1963, 71, 586-88.

Fisher, Franklin M., "Embodied Technical Change and the Existence of an Aggregate Capital Stock," Review of Economic Studies, 1965, 32, 263-88.

Gordon, Robert J., The Measurement of Durable Goods Prices, Chicago: University of Chicago Press for the National Bureau of Economic Research, 1990.

Gort, Michael and Boddy, Raford, "Vintage Effects and the Time Path of Investment in Production Relations," in Murray Brown, ed., The Theory and Empirical Analysis of Production, Studies in Income and Wealth, Volume 31, New York: Columbia University Press for the National Bureau of Economic Research, 1967, 395-422.

Gregory R.G., and James, Denis W., "Do New Factories Embody Best Practice Technology?," The Economic Journal, December 1973, 1133-1155.

Griliches, Zvi, "Hedonic Price Indexes for Automobiles: An Econometric Analysis of Quality Change," in, The Price Statistics of the Federal Government, New York: National Bureau of Economic Research, General Series, No. 73, 1961, 137-196.

________, "Production Functions in Manufacturing: Some Preliminary Results," in Murray Brown, ed., The Theory and Empirical Analysis of Production, Studies in Income and Wealth, Volume 31, New York: Columbia University Press for the National Bureau of Economic Research, 1967, 275-322.

________, "Comment on 'Quality Adjustments in the Producer Price Indexes'," in Murray F. Foss, ed., The National Income and Product Accounts: Selected Topics, Studies in Income and Wealth, Volume 47, Chicago: University of Chicago Press for the National Bureau of Economic Research (1983), 142-145.

Gullickson, William and Harper, Michael J., "Multifactor Productivity in U.S. Manufacturing, 1949-83," Monthly Labor Review, October 1987, 18-28.

Hall, Robert E., "Technical Change and Capital From the Point of View of the Dual," Review of Economic Studies, 1968, 35, 34-46.

________, "The Measurement of Quality Change From Vintage Price Data," in Zvi Griliches, ed. Price Indexes and Quality Change, Cambridge, MA: Harvard University Press, 1971.

Hulten, Charles R, "The Measurement of Capital," in Ernst R. Berndt and Jack E. Triplett, eds., Fifty Years of Economic Measurement, Studies in Income and Wealth, Volume 54, Chicago: Chicago University Press for the National Bureau of Economic Research, 1990, 119-152.

Intriligator, Michael D., "Embodied Technical Change and Productivity in the United States 1929-1958," Review of Economics and Statistics , 1965, 47,65-70.

Johansen, Leif, "Substitution versus Fixed Production Coefficients in the Theory of Economic Growth: A Synthesis," Econometrica, April 1959, 27,157-176.

Jorgenson, Dale W., "The Embodiment Hypothesis," Journal of Political Economy, February 1966, 74, 1-17.

________, and Griliches, Zvi, "The Explanation of productivity Change," Review of Economic Studies, July 1967, 34, 349-83.

________, Gollop, Frank M., and Fraumeni, Barbara M., Productivity and U.S. Economic Growth, Cambridge, MA: The Harvard University Press, 1987.

Kendrick, John W., Productivity Trends in the United States, New York: National Bureau of Economic Research, 1961.

Leontief, Wassily W., "Introduction to a Theory of the Internal Structure of Functional Relationships," Econometrica, October 1947, 15, 361-373.

Matthews, R.C.O., "'The New View of Investment': Comment," Quarterly Journal of Economics, February 1964, 78, 165-172.

Nelson, Richard R., "Aggregate Production Functions and Medium Range Projections," American Economic Review, September 1964, 54, 575-606.

Phelps, Edmund S., "The New View of Investment: A Neoclassical Analysis," Quarterly Journal of Economics, November 1962, 76, 548-567.

________, and Yaari, M.E., "Reply to Matthews," Quarterly Journal of Economics, February 1964, 78, 172-176.

Salter, W.E.G., Productivity and Technical Change, Cambridge: Cambridge University Press, 1960.

Solow, Robert M., "Technical Change and the Aggregate Production Function," Review of Economics and Statistics, August 1957, 39, 312-320.

________, "Investment and Technical Progress," in K.Arrow, S. Karlin and P. Suppes, eds., Mathematical Methods in the Social Sciences. 1959, Stanford: Stanford University Press, 1960.

Triplett, Jack E., "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, Volume 47, Chicago: University of Chicago Press for the National Bureau of Economic Research, 1983, 296-311.

________, "Hedonic Functions and Hedonic Indexes," in John Eatwell, Murray Milgate and Peter Newman, eds., The New Palgrave Dictionary of Economics, Vol. 2, New York: The Macmillan Press Limited, 1987, 630-634.

U.S. Department of Commerce, Bureau of Economic Analysis, Fixed Reproducible Tangible Wealth in the United States, 1925-85, Washington D.C.: USGPO, June 1987.

U.S. Department of Labor, Bureau of Labor Statistics, Trends in Multifactor Productivity, 1948-81, Bulletin 2178, Washington D.C.: USGPO, September 1983.

Appendix Table A1 - Parameters of Embodied Technical Change by Type of Equipment, 1949-1983

BLS Equipment Class	Average[a] Income Share $\pi(t)$	Embodied[b] Technical Change $\phi(t)$	Average[c] Embodied Efficiency $\psi(t)$	Elasticity[d] of Embodiment $\varepsilon(t)$
Furniture & Fixtures	2.54	1.25	1.02	0.08
Fabricated Metal Products	7.45	2.19	2.03	0.17
Engines & Turbines	0.47	4.05	3.57	0.43
Construction Equipment	0.13	2.18	1.99	0.15
Metalworking Equipment	20.60	2.02	1.68	0.14
Special Industry Equipment	22.36	4.88	3.90	0.36
General Industry Equipment	17.23	2.24	1.89	0.17
Office Computing Equipment	7.39	11.39	10.50	0.50
Service Industry Equipment	1.06	4.23	3.23	0.29
Communications Equipment	0.87	6.68	5.38	0.34
Electric Transmission Eq.	8.27	2.18	1.93	0.21
Household Electric Eq.	0.40	1.40	0.89	0.07
Trucks	3.74	2.82	2.46	0.14
Autos	3.83	1.24	1.11	0.08
Scientific & Engineering	1.92	5.47	5.33	0.28
Copy Equipment	1.57	3.22	2.95	0.09
Other Equipment	0.15	1.81	1.46	0.13
All Equipment	100.00	3.44[e]	3.00[e]	0.23[e]

Sources: See notes at end of table.

Appendix Table A1 - Parameters of Embodied Technical Change by Type of Equipment, 1949-1973

BLS Equipment Class	Average[a] Share 1949-73 $\pi(t)$	Embodied[b] Technical Change $\phi(t)$	Average[c] Embodied Efficiency $\psi(t)$	Elasticity[d] of Embodiment $\varepsilon(t)$
Furniture & Fixtures	2.71	1.38	0.94	0.07
Fabricated Metal Products	7.53	2.92	2.55	0.22
Engines & Turbines	0.48	5.65	4.45	0.55
Construction Equipment	0.15	2.36	1.92	0.15
Metalworking Equipment	20.93	2.12	1.84	0.16
Special Industry Equipment	22.71	4.73	3.86	0.33
General Industry Equipment	17.67	2.19	1.67	0.16
Office Computing Equipment	6.06	12.66	11.52	0.61
Service Industry Equipment	1.33	4.18	3.66	0.28
Communications Equipment	0.84	5.82	5.06	0.36
Electric Transmission Eq.	8.72	2.65	2.12	0.23
Household Electric Eq.	0.47	0.96	0.85	0.07
Trucks	3.64	3.00	2.62	0.15
Autos	4.29	1.49	1.22	0.09
Scientific & Engineering	1.65	4.83	3.17	0.21
Copy Equipment	0.67	2.33	1.62	0.05
Other Equipment	0.15	1.78	1.61	0.16
All Equipment	100.00	3.43[e]	2.91[e]	0.23[e]

Sources: See notes at end of table.

Appendix Table A1 - Parameters of Embodied Technical Change by Type of Equipment, 1974-1983

BLS Equipment Class	Average[a/] Share 1974-83 $\pi(t)$	Embodied[b/] Technical Change $\phi(t)$	Average[c/] Embodied Efficiency $\psi(t)$	Elasticity[d/] of Embodiment $\varepsilon(t)$
Furniture & Fixtures	2.13	0.93	1.22	0.10
Fabricated Metal Products	7.25	0.44	0.78	0.06
Engines & Turbines	0.46	0.22	1.45	0.17
Construction Equipment	0.09	1.75	2.14	0.15
Metalworking Equipment	17.79	1.78	1.29	0.12
Special Industry Equipment	21.49	5.23	3.99	0.42
General Industry Equipment	16.13	2.38	2.40	0.21
Office Computing Equipment	10.72	8.34	8.05	0.25
Service Industry Equipment	0.37	4.35	2.19	0.32
Communications Equipment	0.94	8.74	6.14	0.29
Electric Transmission Eq.	7.15	1.06	1.46	0.15
Household Electric Eq.	0.20	2.45	1.00	0.07
Trucks	3.99	2.39	2.08	0.11
Autos	2.69	0.65	0.87	0.06
Scientific & Engineering	2.61	8.71	10.53	0.44
Copy Equipment	3.82	5.36	6.15	0.20
Other Equipment	0.16	1.90	1.08	0.08
All Equipment	100.00	3.47[e/]	3.20[e/]	0.22[e/]

Sources: See notes at end of table.

Notes to Appendix Table A1

a. $\pi(t)$: The share of each class in total income accruing to equipment (arithmetic average over time, in percentage points); source: BLS data underlying Gullickson and Harper (1987).

b. $\phi(t)$: The average annual arithmetic growth rate of the index of best practice technical efficiency $\Phi(t)$; computed from equation (5c) of the text using BLS investment price indexes and quality-adjusted investment price indexes based on Gordon (1990); arithmetic averages are used in these calculations to facilitate comparison with the discrete-time elasticity of embodiment $\varepsilon(t)$; the ϕ's implicit in Tables 3, 4, and 5 preserve the Tornqvist logarithmic growth rates.

c. $\psi(t)$: The average annual arithmetic growth rate of the index of average embodied technical efficiency, $\psi(t)$; computed from equation (5b) of the text using BLS capital stocks and quality-adjusted capital stocks computed from equation (3) of the text using BLS data and estimates of $\Psi(t)$; arithmetic averages are used in these calculations to facilitate comparison with the discrete-time elasticity of embodiment $\varepsilon(t)$; the ψ's implicit in Tables 3, 4, and 5 preserve the Tornqvist logarithmic growth rates.

d. $\varepsilon(t)$: The elasticity of embodiment ($\varepsilon = 1$ for the unit elasticity); computed from equation (12) of the text using estimates of $\Phi(t)$ and $\Psi(t)$ described in preceding notes.

e. The all-equipment totals computed as the arithmetic average of the of the annual income-share weighted average across the seventeen equipment classes, using the $\pi(t)$ weights for each class in each year.