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R&D, UNMEASURED QUALITY CHANGE, AND PRODUCTIVITY GROWTH

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Economists believe that unobserved improvements in capital quality cannot explain the productivity residual because higher capital inputs are offset by a greater output of investment goods. The present paper examines a third step in this chain of reasoning. If the output of investment goods grows more rapidly because of measurement error, the implied return to R&D in the research-intensive capital goods sector increases sharply. When output and inputs in the capital goods sector are adjusted to allow for Gordon's quality change, the additional direct return to R&D is very high, typically 75 percent or more. The measurement error taking place upstream is large enough to account for the high indirect returns to R&D often attributed to downstream users. These results imply that indirect R&D is an important source of economic growth, and can explain portions of output growth normally left in the residual.

JEL categories O3, O4.

Unmeasured quality change is an important concept which by its essential nature is very difficult to get a handle on. Most of the concern about unmeasured quality change has occurred in the context of consumer prices, where little definitive information is available. However, in the context of capital goods, Gordon (1990) has prepared extremely detailed estimates of the error contained in the prices of many specific goods.

This paper treats the difference between Gordon's deflators and the standard deflators of capital goods as an indication of the presence of unmeasured quality change. The paper then proceeds to examine the role of R&D in unmeasured quality change, and the implications which the connection between R&D and errors in price measurement has for understanding the role of R&D in the economy.

Gordon's (1990) study of capital goods concludes that there is substantial unmeasured quality change, which is particularly influential in such high-tech assets as computers, communication equipment, and aircraft.[1] The present paper examines how our understanding of the rate of return to R&D is altered if Gordon's results are accepted.

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1 Gordon's study examined the specific characteristics of a large number of capital goods, and prepared summary measures of the unmeasured quality change taking place in each of twenty-two different types of capital equipment in every year between 1947 and 1983. While Gordon's careful work on quality change provides the best estimates to date, some concern has also been expressed concerning the reliability of Gordon's proposed alternative measures (Triplett (1993)).

Gordon treated his results as an index of unmeasured quality change, and the Boskin Commission Report (1996) relied on Gordon's work at several points in their evaluation of the importance of quality change. However, the Boskin Commission (page 33) also pointed out that Gordon's results to some extent inevitably also reflect the influence of substitution or formula bias.

Throughout this paper we refer to the Gordon measures as an index of unmeasured quality change. In view of the comment from the Boskin Commission cited above, actual quality change must be considered to account for only a portion of the total Gordon measures.

Hulten (1992) and Greenwood, Hercowitz and Krusell (1997) are other studies examining the impact that Gordon's work has on the understanding of economic growth. Moulton (1996, page 171) points out that Gordon's results are less relevant for the current bias in the CPI, since the Bureau of Labor Statistics has altered its procedures for computing price changes. However, the entire record of previous error in the price indices, throughout all past years, is directly relevant for productivity purposes.

Output, capital inputs, and materials inputs in the capital goods sector are each redefined to reflect Gordon's evidence on hidden quality change. When these adjustments are made, the rate of return to R&D in the production of capital goods increases sharply. The additional rate of return to R&D is remarkably high, typically 75 percentage points or more.

These results have several interesting implications. First, they suggest that the rapid advances of technology associated with R&D bring about much of the measurement error which exists in prices. Second, Gordon's work suggests that output prices in the computer and information technology industries contain substantial measurement error. However, these large errors reflect the underlying presence of R&D. In most, though not all, of the evidence considered, once the typical effects of R&D on price measurement error are taken into account, the remaining measurement error is not especially strong in the computer or information technology industries. Third, if measurement error occurs in output prices, it is difficult to discriminate between the direct and indirect effects of R&D. The same productivity gain can be understood either as a direct return to R&D in the capital goods sector or as an indirect return to R&D in downstream industries which purchase capital goods. Fourth, unmeasured quality change can in fact reduce the residual. Since Jorgenson's (1966) paper, economists have understood that, if unmeasured quality change exists, the increase in capital inputs is offset by an increase in investment goods output, so that there is little change in the overall residual. However, if, contrary to Jorgenson's analysis, R&D is treated as an additional factor in production, a further effect comes into play. If more output is attributed to inputs, which unlike Jorgenson now include R&D, less is left over to be ascribed to technical change, and the residual declines. R&D operating through this further or indirect channel is estimated to have contributed 0.2 percent a year to 1947-87 national productivity growth. Such results indicate that indirect R&D contributed more to growth, over this period, than BLS measures of direct R&D or of human capital (the education and experience of the work force) did.

The analysis helps to clarify and integrate several issues which have appeared in the recent literature. First, unmeasured quality change is an important issue (Report of the Advisory Commision To Study The Consumer Price Index (Boskin <u>et al</u>. (1996))), which requires a much greater depth of understanding. The present analysis suggests that, at least within the capital goods industries studied by Gordon, the measurement error contained in prices is likely to be most substantial in the most highly research intensive industries where rapid technological change occurs. Such patterns support the view that unmeasured quality change and new goods are important elements in bringing about price error.

Several previous studies (Lichtenberg and Griliches (1989); Siegel (1994)), have examined the role of R&D in unmeasured quality change. Lichtenberg and Griliches (1989, page 7) suggest that "the major cause of quality change is product-oriented R&D expenditures undertaken by industry".[2] The present study deals with changes in the R&D stock over time, which is a strongly preferable concept to the level of R&D expenditures in a single year, the measure used in previous studies. The results show that the rapid technological change associated with growth in the R&D stock is indeed a major cause of unobserved quality change. The analysis also shows that, since much of the impact of R&D is not reflected within current economic statistics, important portions of the direct economic role of R&D have systematically been understated.

Several recent discussions have emphasized the economic role of computers and information technology (IT) (Morrison (1997)). The suggestion is that computers and IT have a greater impact on productivity growth than investment in other forms of equipment.[3] This paper shows that R&D is the central factor underlying unmeasured quality change. Unmeasured quality change has in fact been substantial in computers and IT, but, in most of the

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[2] The present study uses information on stocks of total R&D, including both product and process R&D. No corresponding information is available on product R&D. However, Scherer (1984) has shown that, as one might expect, the great majority of R&D conducted in capital goods sectors consists of product R&D.

[3] More broadly, DeLong and Summers (1991) suggest that equipment in general contributes more to growth than other forms of capital do. Unmeasured quality change could plausibly create such an effect.

evidence examined here, unmeasured quality change in these assets is no greater than the R&D contained in them would suggest.

On a further topic, Nadiri's (1993) review of the relevant literature has shown that downstream industries benefit from research conducted by upstream producers. At present, it is an open question whether these gains reflect genuine knowledge transfer or difficulties in price measurement (Griliches (1992)). The present analysis shows that the increased returns to R&D found upstream in the capital goods sector, once output and inputs are adjusted for hidden quality change, are approximately equivalent to the downstream returns to R&D reported by Nadiri. The correspondence between the empirical estimates of these two different facets of the indirect return to R&D suggests that the observed downstream returns to R&D primarily represent measurement error.

Most importantly, many empirical studies, reviewed in Griliches (1992) and Nadiri (1993), suggest indirect R&D has been an important source of productivity growth. However, this empirical literature has never adequately addressed Jorgenson's (1966) contention that unmeasured improvements in capital quality cannot explain the productivity residual because higher capital inputs are offset by a greater output of investment goods. This paper introduces a third step into such a chain of reasoning. If output growth in the capital goods industries has been greater than previously realized, the added output is not manna from heaven, as implied by Jorgenson's procedure, but instead reflects the heavy R&D occurring in the capital goods sector. Using the estimates of quality improvement in capital goods provided by Gordon (1990), we demonstrate that much of the added output implied by Gordon's data can be attributed to R&D. Since more of output growth is thereby assigned to inputs, which, contrary to Jorgenson, now include R&D, less is left over as a residual. From this point of view, the indirect R&D effect reflects a real, previously unmeasured, contribution of (upstream) R&D and can therefore help explain productivity growth and the residual. As discussed in Section I, when the link between increased capital goods output and R&D is taken into account, the indirect R&D studies unambiguously help explain the residual; without the link between Gordon's work and R&D, it is not possible to establish a definite real effect of indirect R&D on the residual.

Section I below outlines the theoretical structure used in the present study, which includes the standard version of the R&D model. Section II deals briefly with data issues, essentially summarizing how R&D stocks are created for each of the capital goods industries. Section III provides empirical results, Section IV considers the implications of the results, and Section V contains the conclusions.

I. Introduction and Theoretical Structure.

Economists have long been interested in the relationship between technical progress and capital investment. The embodiment model (Solow (1960)), in which technical progress is embodied in new vintages of capital, has been perhaps the most successful attempt to address this issue. Embodiment might seem to suggest an increased amount of capital inputs, which would make it possible to reduce the implied residual. However, in an extremely influential contribution Jorgenson (1966) showed that unmeasured improvements in the quality of capital goods were also associated with an increase in the output of investment goods, which tended to increase the implied residual. Since the effects of increased capital inputs and increased investment goods output approximately offset each other, technical change embodied in capital goods does not alter the unexplained residual.

The present paper introduces a third step into this line of reasoning. R&D is examined as an additional input. If the output of capital goods does in fact increase more rapidly than previously considered, this additional output implies a much greater direct return to research in the highly research-intensive capital goods sector. In turn, a greater portion of output growth can be attributed to the observed inputs, which now include research, and less of output remains to be explained by the residual. Consequently, the Jorgenson critique can be overcome and quality improvements embodied in capital can reduce the unexplained residual. To the extent that unmeasured quality improvement in capital can be attributed to R&D, these expanded effects of R&D can help reduce the observed residual.[4]

IA. Theoretical Structure.

Assume that production takes place in two industries, an upstream industry which produces a technologically sophisticated product, such as capital or materials, and a downstream industry which uses the entire output of the upstream industry in its own production. To avoid the distinction between stocks and flows, we assume that the entire production of the upstream industry is used in the current period.

Output growth in the upstream industry (u) is:

$$\dot{Y}^u = \alpha_L{}^u\dot{L}^u + \alpha_M{}^u\dot{M}^u + \alpha_R{}^u\dot{R}^u + \dot{\theta}^u \qquad (1)$$

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4 Jorgenson's (1966) formal model is of course entirely correct. The Jorgenson model assumes that there are only two inputs, capital and labor, and that these factor shares add up to one. A third factor, such as R&D, is therefore excluded from the analysis. It is completely understandable that R&D would be omitted, since the R&D literature was very sparse in 1966.

In addition, the analysis in Section IA of the present paper, which shows that the R&D effect can alternatively be assigned to either direct R&D or indirect R&D, depending upon whether the Gordon deflators or the the official investment deflators are used, is essentially a particular example of Jorgenson's more general argument that any given technical change can be interpreted alternatively as embodied or disembodied technical change. The new theme of the present paper is that we now know that measurement error is innately associated with R&D, and that this new connection, when placed in the context of the unmeasured quality change debate, implies that R&D contributes more to multifactor productivity growth than has previously been realized.

in which $\dot{Y}^u$ is the growth of output, $\dot{L}^u$ the growth of labor, and $\dot{M}^u$ the growth of materials in the upstream industry. $\dot{R}^u$ is the growth of research. $\alpha_L{}^u$, $\alpha_M{}^u$, and $\alpha_R{}^u$ are the respective factor shares. As in most empirical discussion of R&D in the United States, α_R reflects the social return to research, so that $\alpha_L + \alpha_M = 1$. $\dot{\theta}^u$ is the rate of multifactor productivity growth in the upstream industry. Multifactor productivity is the residual after the effects of labor, materials, and research are removed.

Production downstream (d) is closely similar:

$$\dot{Y}^d = \alpha_L{}^d \dot{L}^d + [\alpha_M{}^d \dot{M}^d + \alpha_U{}^d \dot{Y}^u] + \dot{\theta}^d \qquad (2)$$

The downstream industry does no research of its own and uses the entire output of the upstream industry (Y^u). $\alpha_L{}^d$, $\alpha_M{}^d$, and $\alpha_U{}^d$ are the factor shares in this industry. $\dot{\theta}^d$ is multifactor productivity growth in the downstream industry.

Productivity can be measured for the sum of the upstream and downstream industries. Total output is the sum of the output in the two industries. Therefore, economywide productivity growth is $s_u\dot{\theta}_u + (1-s_u)\dot{\theta}_d$, where s_u is the upstream industry's value share of total output and $(1-s_u)$ is the downstream industry's value share.

The value of output in the upstream industry is equal to the amount of sophisticated materials which the downstream industry purchases from the upstream industry. The value share of the upstream industry in the production of the downstream industry is therefore $s_u/(1-s_u)$; since these coefficients reflect value shares, they are unaltered if the implied price of upstream output, Y^u, changes. Similarly, the shares in equation (1) reflect the shares of labor and materials; these are likewise unaltered if the rate of return to R&D, an externality, changes.

Consider now an alternative scenario in which further technical progress, not initially measured, occurs in the upstream product at the rate g. Equation (1) becomes:

$$\dot{Y}^{u*} = \alpha_L{}^u\dot{L}^u + \alpha_M{}^u\dot{M}^u + \alpha_R{}^u\dot{R}^u + \dot{\theta}^u + \dot{g} \qquad (3)$$

where $\dot{Y}_u{}^*$ reflects the more rapid growth of output in this industry. Productivity growth in the upstream industry is now $\dot{\theta}^u + \dot{g}$.

The input of upstream production used in the downstream industry similarly increases at the rate $\dot{g}$. Downstream production is therefore:

$$\dot{Y}^d = \alpha_L{}^d\dot{L}^d + [\alpha_M{}^d\dot{M}^d + \alpha_U{}^d\dot{Y}^{u*}] + \dot{\theta}^{d*} \qquad (4)$$

$\dot{\theta}^{d*}$ is the new rate of productivity growth in the downstream industry and is equal to $\dot{\theta}^d - \alpha_U{}^d\,\dot{g}$ to reflect the greater input growth.

Total productivity growth in the economy is now $s_u(\dot{\theta}^u+\dot{g})$ +

$(1-s_u)(\dot{\theta}^d - \alpha_U{}^d\dot{g})$. In equation (2) above the corresponding productivity growth was $(s_u\dot{\theta}_u + (1-s_u)\dot{\theta}_d)$. The Jorgenson effect is $s_u\dot{g}$, the increase in productivity growth due to the greater investment output. The Solow effect is $(1-s_u)(-\alpha_U{}^d\dot{g})$, the decline in productivity growth due to increased capital formation. Since $\alpha_U{}^d = s_u/(1-s_u)$, these two effects offset each other here, and there is no effect on the productivity trend.

Consider now the case in which production is still described by equations (1) and (2), but unmeasured quality change occurs in the upstream industry because of technical change associated with R&D. Under these circumstances, corrected output growth in the upstream industry, $\dot{Y}^{u+}$, is:

$$\dot{Y}^{u+} \quad = \quad \dot{Y}^u + b\,\dot{R}_u \tag{5}$$

Production growth in the upstream industry, as given by equation (1), then becomes:

$$\dot{Y}^{u+} = \alpha_L{}^u\dot{L}^u + \alpha_M{}^u\dot{M}^u + (\alpha_R{}^u + b)\dot{R}^u + \dot{\theta}^u \tag{6}$$

Observed productivity growth in the upstream industry is still $\dot{\theta}^u$, because the additional measured output in this industry is now attributed to $\dot{R}^u$. In the downstream industry production is:

$$\dot{Y}^d = \alpha_L{}^d\dot{L}^d + [\alpha_M{}^d\dot{M}^d + \alpha_U{}^d\dot{Y}^{u+}] + \dot{\theta}^{d+} \tag{7}$$

Productivity growth in the downstream industry, $\dot{\theta}^{d+}$, is now equal to $\dot{\theta}^d - \alpha_U{}^d b\dot{R}^u$, in terms of equation (6), to reflect the higher measured input growth. Consequently, productivity growth in the total economy is now $s_u\dot{\theta}_u + (1-s_u)(\dot{\theta}_d - \alpha_U{}^d b\dot{R}^u)$, which is $(1-s_u)(-\alpha_U{}^d b\dot{R}^u)$ lower than in the base case. In essence, since the output gains in the upstream industry have been attributed to an input, R&D, the Jorgenson effect does not offset the Solow effect, and productivity growth in the total economy decreases.

This interpretation of equations (6) and (7) is central to our analysis. As in equations (3) and (4), upstream output once more increases when the deflators are corrected. However, this additional output is now attributed to R&D, essentially because the measurement error in the deflators has systematically missed the rapid technical change taking place in the most R&D intensive industries. Consequently, the increased upstream output now does not affect the upstream residual. As a result, the overall residual is lower as well. Section III below demonstrates that this case, in which additional upstream output is attributed to R&D, is empirically relevant.

To put the matter in a slightly different way, in Jorgenson's (1966) model, the increased output which appears in the capital goods sector due to the correction of measurement error is manna from heaven, not attributed to any specific input. In contrast, in our framework part of the increased output is attributed to R&D. Since the return to R&D is an externality, which depends on R&D's contribution to the associated growth of productivity, as in equation (8) below, it is quite reasonable that the implied return to R&D will increase sharply if output and productivity in the capital goods sector both grow more rapidly than previously realized.

Equations (6) and (7) also illustrate that the effects of indirect R&D can, under these circumstances, be assigned to either direct or indirect R&D. If upstream output is quality corrected, the contribution of R&D to output growth is $s_u \alpha_R{}^u \dot{R}^u + s_u b \dot{R}^u$ from the upstream industry and zero from the downstream industry. All the effect of R&D is direct and none is indirect. On the other hand, if quality change and price errors are ignored, then the additional return to research, b, is unobservable in the upstream industry, but appears instead in the downstream industry as higher MFP growth. Under these circumstances, the direct contribution of research is $s_u \alpha_R{}^u \dot{R}^u$ and the indirect contribution to total output is $(1-s_u)(\alpha_U{}^d b\dot{R}^u)$, which, since $\alpha_U{}^d = s_u/(1-s_u)$, is also equal to $s_u b \dot{R}^u$. The total contribution remains the same, but in this case is divided among the direct and indirect effects in the proportions shown.

The above discussion illustrates a sense in which part of the returns to R&D can be measured as either direct or indirect returns. If the conventional deflators are inaccurate, so that output growth in the upstream industry and input growth in the downstream industry are both understated, the productivity growth observed in the downstream industry is actually $\alpha_U{}^d b\dot{R}^u$ higher than true productivity. On the other hand, if the relevant deflators are accurate, an equivalent term will appear as part of the larger direct return to upstream research.

Note that the frequent empirical reports that indirect R&D is associated with productivity growth, summarized in Griliches (1992) and Nadiri (1993)) are not in themselves sufficient to establish that indirect R&D is a genuine contributor to productivity growth. Such reports are still consistent with equations (3) and (4), in which indirect R&D reflects measurement error rather than any real influence on productivity growth. On the other hand, further collateral evidence that indirect R&D reflects previously unmeasured upstream productivity gains, as reported in Section III of the present paper, changes the situation greatly. It then becomes clear that equations (6) and (7) are relevant, and that the reported indirect R&D effect actually reflects genuine, previously unrecognized, further returns to (upstream) R&D and can therefore, quite legitimately, explain a further component of productivity growth and reduce the unexplained residual.

Finally, the expression $\alpha_U{}^d b\dot{R}^u$ by which downstream productivity growth is overstated due to measurement error can be restated in other terms. $\alpha_U{}^d$, the share of purchases from the upstream industry in the output of the downstream industry, is equal to Y^u/Y^d. The elasticity b can be rewritten as the cost share r_{RD} (RD/Y_u), where r_{RD} is the additional direct rate of return to R&D in equation (6) and RD is the <u>level</u> of the R&D

stock in the upstream industry. Finally, $\dot{R}^u$ can be restated as $\Delta RD/RD$, where ΔRD is the change in the upstream R&D stock. Combining these terms, if inaccurate deflators are used, true productivity in the downstream industry is overstated by:

$$(Y^u/Y^d) * (r_{RD}\ (RD/Y_u)) * (\Delta RD/RD)$$

which is equivalent to $r_{RD}\ \Delta RD/Y^d$. Since the change in the upstream R&D stock is allocated to the downstream industry, ΔRD is also the change in the downstream (indirect) R&D stock. Note that the expression $\Delta RD/Y^d$ shows the change in R&D purchased indirectly from the upstream industry divided by downstream industry output. This expression is exactly the independent variable which has traditionally been used to estimate the indirect return to research. Specifically, the indirect return to research has usually been estimated from the relationship:

$$\dot{A}/A \quad = \quad a \quad + \quad b\ \Delta RD/Y^d$$

in which $\dot{A}/A$ is the rate of multifactor productivity growth in the downstream industry, and ΔRD is the change in the indirect R&D stock. The estimate of b from this equation provides the standard estimate of r_{RD}, the rate of return to indirect R&D.

Of course, in reality the downstream R&D stock is an inherently more complex concept, which also depends on the pattern of depreciation within many different capital assets of different vintages. Nevertheless, it is clear that, even when depreciation complicates the picture, if the acquisition of new capital assets brings greater technological advantages than the deflators convey, and if increases in indirect R&D can approximate the unmeasured quality change contained in these new assets, then measures of the increase in indirect R&D will be associated with downstream productivity advantages.

IB. Empirical Implementation.

The empirical analysis is conducted using the standard R&D stock model which has typically been used to analyze the relationship betweeen R&D and productivity growth. According to this model, the annual rate of multifactor productivity, $\dot{A}/A$, is composed of two terms, a constant term plus an additional term expressing $\Delta\overline{RD}$, the increase in the R&D stock between years t and t-1, divided by Y_{t-1}, the previous year's output, measured in constant dollars.[5] Specifically:

$$(\dot{A}/A) = a + b\ (\Delta RD/Y_{t-1}) \qquad (8)$$

The coefficient b provides an estimate of the rate of return to R&D.

The expression $\Delta RD/Y_{t-1}$ is used throughout this paper as a (normalized) measure of the increase in R&D. To determine the

5 Output is measured in constant dollars, rather than by a superlative index, because the information needed to construct a superlative index is not available for 1947 to 1958. We used constant dollar output measures to ensure that a consistent series was available throughout the period examined. For the 1958-83 period. it is possible to calculate a Tornquist index of output. In the results of line (3) of Table 4, the estimate of the effect of R&D changes only from .729 with a constant dollar index of output to .724 with a Tornquist index of output. The alternative output measure has little effect on the results.

increase in R&D over time periods longer than a year, we first define the annual increase in R&D, r_j, as:

$$r_j = \Delta RD/Y_{t-1}$$

and then calculate the long-term increase in R&D, R_{LT}, as:

$$R_{LT} = \left(\prod_{j=1}^{n} (1.0 + r_j) \right)^{1/n} - 1.0 \qquad (9)$$

that is, as the geometric mean of $(1.0 + r_j)$ less one.

The multifactor residual, the dependent variable in equation (8), is obtained from the relationship:

$$\dot{A}/A = \dot{Y}/Y - \alpha_k \dot{K}/K - \alpha_l \dot{L}/L - \alpha_m \dot{M}/M \qquad (10)$$

in which $\dot{A}/A$ is multifactor productivity growth, Y is output, K is capital input, L is labor input, and M is materials input. α_k, α_l, and α_m are the respective factor shares.

The result of Gordon's work is a series of estimates of the annual drift or error in the official deflators for each asset i in year j, $(\dot{G}/G)_{ij}$. We assume that, although Gordon has constructed his measures of price drift only for capital goods, that the same drift factors can also be applied to the total output of the industry, including deliveries to other customers, from each of these capital goods industries.[6]

[6] Alternatively, one could attempt to analyze only the capital goods portion of each industry. In this case, one would have to approximate the factor inputs used in capital goods production, perhaps from the ratio of capital goods output to total output.

Consider now the impact which Gordon's unmeasured quality change has on standard measures of $\dot{A}/A$ such as those shown in equation (10). Assume that the quality of output increases at the rate $(\dot{G}/G)_{ij}$. Then true output growth also increases by $(\dot{G}/G)_{ij}$ and is now $(\dot{Y}/Y)_{ij} + (\dot{G}/G)_{ij}$. However, these quality increases also imply some increases in the inputs of both capital and materials. Consequently, both $(\dot{K}/K)_{ij}$ and $(\dot{M}/M)_{ij}$ also increase, and so a $(\dot{G}/G)_{ij}$ increase in output, due to Gordon's drift, increases $(\dot{A}/A)_{ij}$ in equation (10) by somewhat less than $(\dot{G}/G)_{ij}$.

There are three reasons why measured inputs are likely to increase when the output of capital goods industries is reevaluated. First, all industries purchase materials from themselves, often in large amounts. If unmeasured quality change occurs in output, it will similarly appear within these self-purchases of materials.

Capital goods industries often provide output to consumption and government and provide materials to other industries in addition to their role as producers of capital goods. The increase in goods supplied directly to consumers, such as automobiles and home appliances, would tend to increase production and productivity. However, the increase in materials inputs would tend to reduce productivity growth in the recipient industries. Since we are essentially interested in calculating the effect of the Gordon deflator on capital goods production, we do not explore the productivity implications of the Gordon deflators in these further contexts.

Second, capital goods industries also purchase some materials from the other industries which are capital goods suppliers. If output growth in these other capital goods industries is adjusted to reflect unmeasured quality change, the materials purchased from these industries will also increase more rapidly.

Third, if the equipment deflator is changed to reflect Gordon's unmeasured quality change, the implied growth of the equipment stock increases substantially. However, stocks of structures and inventories remain unchanged. In addition, the overall property share is relatively low, so the reevaluation of equipment stocks typically does not have a large impact on the implied growth of productivity.

Let $(\dot{A}_G/A_G)_{ij}$ be the additional increase in multifactor productivity due to the Gordon increase in output growth, less the associated increases in capital and materials inputs. Appendix A describes the procedures through which $(\dot{G}/G)_{ij}$ is adjusted to reflect changes in M and K, and thereby obtain $(\dot{A}_G/A_G)_{ij}$. Then, through a methodology parallel to equation (8), the additional rate of return to R&D, b', which appears solely due to the Gordon quality changes, is:

$$(\dot{A}_G/A_G)_{ij} \quad = \quad a \quad + \quad b' \quad (\Delta RD/Y_{t-1})_{ij} \tag{11}$$

b' provides an estimate of the increase in the rate of return to R&D due solely to the measurement error suggested by Gordon.[7]

For those years in which information on both $\dot{A}/A$ and $\dot{A}_G/A_G$ is available, it is feasible to compare the estimates of b from equation (8) and b' from equation (11) in order to determine the relative importance of the standard direct return to research and of the supplementary return to R&D associated with the Gordon effect.

II. Data Issues.

Gordon prepared capital goods deflators for twenty-two types of assets for every year between 1947 and 1983. We obtained measures of the privately financed R&D stock contained in each of the corresponding industries in every year from two companion papers (Sveikauskas (a,b forthcoming)), which calculated the R&D stocks contained within capital equipment and within materials purchases in a wide variety of industries. These stocks assume a two-year lag between R&D expenditures and the time in which these enter the research stock. The R&D contained in capital equipment, which is analyzed in the present paper, accounts for

[7] The discussion in subsections A. and B. of Section III below examines the relationship between ($\dot{G}/G$), the growth of the Gordon drift, and R&D, rather than the relationship between ($\dot{A}_G/A_G$) and R&D described in equation (11). We choose to analyze the raw Gordon data (G/G) in these subsections because these particular data (Gordon (1990, page 536) represent the core of Gordon's basic conclusions, and as such have received considerable attention. However, similar conclusions emerge if the analyses conducted in these subsections are instead conducted in terms of the Gordon drift adjusted for the corresponding increases in capital and materials inputs ($\dot{A}_G/A_G$).

approximately 70 percent of the total growth in the stock of indirect R&D ultimately used by downstream industries.

Measures of the 1947 to 1958 R&D stock have so far not been available for different industries. However, Sveikauskas (b, forthcoming) prepared such information at the industry level, based on data collected from the National Research Council's *Directory of Industrial Research Laboratories of the United States* for R&D expenditures for the years from 1921 to 1960. These R&D data were merged with the National Science Foundation applied product field data for R&D expenditures occuring in 1958 and subsequent years. The result provides a consistent series on the R&D stocks used in the production of each type of capital equipment in every year within the 1947 to 1983 period studied by Gordon.

The directories provide a plausible measure of the total research effort in each industry in directory years such as 1946, 1950, 1955, and 1960. However, it is necessary to estimate research expenditures in the intervening years. In addition, it is difficult to determine how much research is privately financed in each industry in each year. Consequently, the R&D stocks are subject to considerable measurement error prior to 1958.

Equation (11) also requires a measure of real output, Y, for each of the asset categories from 1947 to 1983. Measures of shipments in current dollars are collected for the industries representing each asset category from various issues of the Census or Annual Survey of Manufactures. These current dollar measures were converted to real output using the corresponding output price deflator for each industry. Finally, measures of unmeasured quality change are obtained for each asset in every year from Appendix B and C of Gordon (1990).

III. Empirical Analysis.

A. Long-Term Trends.

As a first examination of the data, we simply compare Gordon's estimates of the 1947 to 1983 drift or error in the deflator for each of his capital assets with the corresponding information on the long-term increase in R&D within each asset, as defined by equation (9).[8]

The first column of Table 1 lists the twenty-two different types of capital equipment included in Gordon's book. Column (1) reports Gordon's (1990, page 536) information on the 1947 to 1983 rate of drift or error in the price index for each of these assets.

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8 Later portions of Section III also examine alternative concepts of R&D growth, such as R&D lags greater than two years. The results of subsections A. and B. also typically hold true if such alternative concepts of R&D growth are analyzed instead.

In addition, the measure of R&D growth analyzed in subsections A. and B. of Section III is generally more effective than alternative measures of the level of R&D intensity (such as the average level of the R&D stock relative to output or the ratio of the R&D stock to output in the initial year) in explaining the Gordon drift. These results provide some evidence that the growth of the R&D stock does in fact explain unmeasured quality change better than the level of the R&D stock does.

Table 1

Average Annual Growth Rate of Unmeasured Quality Change and Increases in R&D, by Type of Equipment, 1947-1983.

Asset Class	(1) Unmeasured Quality Change (G/G)	(2) Change in R&D Stock Per Unit of Output ($\Delta RD/Y_{t-1}$)
Furniture	.0141	.0004
Fabricated Metals	.0180	.0016
Engines, turbines	.0353	.0162
Tractors	.0135	.0058
Agr mach, exc tract	.0070	.0067
Construction mach	.0163	.0052
Mining,oilfield mach	.0163	.0076
Metalworking mach	.0115	.0036
Special ind mach	.0248	.0027
General ind mach	.0181	.0046
Computer,account mach	.0932	.0415
Service ind mach	.0315	.0046
Communications equip	.0584	.0212
Electrical trans equip	.0211	.0079
Other elec equip	.0101	.0061
Trucks	.0297	.0096
Autos	.0133	.0080
Aircraft	.0829	.0149
Ships, boats	.0193	.0022
Railroad equip	.0145	.0006
Instruments	.0349	.0143
Other equip	.0199	.0021

Sources: Unmeasured Quality Change from Gordon (1990, page 536).

Research and Development Stocks and Output are described in Sveikauskas (b, forthcoming).

Gordon used the same deflator for construction machinery and for mining and oilfield machinery. Sveikauskas (b, forthcoming) similarly used a single value of the R&D stock to output ratio for each of these assets.

Column (2) of Table 1 reports parallel information on the increase of the R&D stock, as measured by $\Delta RD/Y_{t-1}$, within the same twenty-two industries. Column (2) shows R_{LT} of equation (9), the geometric mean rate of increase in $\Delta RD/Y_{t-1}$ between 1947 and 1983 for each asset.

As Table 1 indicates, the increase in R&D is strongly associated with Gordon's estimate of the rate of unmeasured quality change within each asset. High technology industries such as engines and turbines, computer and accounting machinery, communications equipment, aircraft, and instruments have a rapid growth of R&D, and are exactly the same assets in which Gordon found a high rate of unmeasured quality change. The regression line describing the relationship between the drift in the price error and the measure of the increase in R&D is:

$$\dot{G}/G = \underset{(2.63)}{.0096} + \underset{(7.10)}{2.098}\Delta RD/Y_{t-1} \qquad \begin{array}{l} r^2 \text{ bar} = .702 \\ \text{t ratios} \quad n = 22 \\ \text{SEE} = .0124 \end{array} \qquad \text{(a)}$$

in which $\dot{G}/G$ is Gordon's rate of annual unmeasured quality change for each asset over the entire 1947 to 1983 period and $\Delta RD/Y_{t-1}$ reflects the increase in R&D between 1947 to 1983. A one percent greater increase in R&D is associated with a two percent greater increase in the Gordon deflator. Such figures would imply an additional rate of return to R&D of over 200 percent. This is a remarkably high rate, and shows how strong the relationship between the Gordon drift and R&D is. Furthermore, asset differences in R&D growth can explain more than half of the interindustry variance in Gordon's unmeasured quality change.

As is apparent from Table 1, the computer, accounting and office machinery category is somewhat of an outlier, both in terms of the annual drift in the price measure and in the long-term increase of research and development. Consequently, the relationship stated above is reexamined within just the twenty-one other capital assets. The corresponding result is:

$$\dot{G}/G = \underset{(1.89)}{-.0085} + \underset{(4.50)}{2.285}\Delta RD/Y_{t-1} \qquad \begin{array}{l} r^2 \text{ bar} = .491 \\ t \text{ ratios} \quad n = 21 \\ SEE = .0126 \end{array} \qquad \text{(b)}$$

These results show that the implied effect of R&D on unmeasured quality change is comparable when computers are excluded. Other assets with strong R&D growth, such as engines and turbines, communications equipment, aircraft, and instruments, also have substantial unobserved quality change.

The relationship between R&D growth and unmeasured quality change can also be examined by rank correlation methods, which utilize all of the available information without assigning undue importance to any individual observation. The rank correlation between these two measures is .508, significantly greater than zero at the 95 percent level.[9]

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9 For 22 industries a rank correlation of .359 is significantly greater than zero at the 95 percent level.

The evidence discussed so far shows that standard measures of the industry R&D effect can explain a substantial proportion of the long-term interindustry variance in unmeasured quality change. Much unobserved quality change takes place in exactly those industries in which R&D growth has been most rapid.

B. Medium-Term Trends: Computers and Information Technology.

Gordon (1990, page 536) also reported estimates of unmeasured quality change in the 1947-60, 1960-73 and 1973-83 subperiods. This information provides additional detail which makes it feasible to examine some further issues.[10]

We examine the twenty-two assets in each of the three periods, so that there are sixty-six observations in all. Within this total sample, when dummies are added for computers and for information technology (COMP is computers, and IT, information technology, is defined as communications equipment and instruments, but not computers), equation (a) becomes:

$$\dot{G}/G = \underset{(3.03)}{.0116} + \underset{(4.12)}{1.657}\Delta RD/Y_{t-1} + \underset{(.74)}{.014}COMP + \underset{(.55)}{.006}IT \qquad \bar{r}^2 = .412 \quad (c)$$

t ratios n = 66
SEE = .0229

[10] These medium-range data contain a fair amount of new information. Correlations between Gordon's measures of price drift over the three time periods are:

	1947-60	1960-73	1973-83
1947-60	1.00		
1960-73	.93	1.00	
1973-83	.58	.45	1.00

Table 1 shows that unmeasured quality change is substantial in both computers and information technology. However, equation (c) shows that unmeasured quality change is no greater for computers or IT than for other forms of equipment, once the increase in R&D in each asset is taken into account. This evidence suggests that R&D is the central underlying factor in unmeasured quality change, and that investment in computers and in IT differs from investment in other assets because these forms of capital contain large amounts of R&D, rather than because quality change has inherently been greater within computers and IT.

C. Annual Data: Production Function Analyses.

C.1. Tests Based on Standard Deflators.

This subsection uses annual data, which employs the full detail included in Gordon's series on price drift for each asset.[11] The analysis is based on equation (11). The first set

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[11] As mentioned in footnote 7 above, the analysis in subsection C. examines $(\dot{A}_G/A_G)$, the annual productivity increase due to the Gordon drift, adjusted for the corresponding implied increase in capital and materials inputs. In contrast, subsections A and B analyzed $(\dot{G}/G)$, the widely noted summary measures of the Gordon drift, with no further adjustment.

Gordon's NIPA deflator for aircraft jumped from .31 in 1947, to .82 in 1948 and fell back to .41 in 1949. NIPA publications on the implicit price deflator, such as Table VII-15 of U.S. Department of Commerce (1958) or Table 7.20 of U.S. Department of Commerce (1981), do not show such drastic changes in the implicit deflator for aircraft during this period. Consequently, we select .37 as the NIPA deflator for aircraft in 1948, obtained by interpolation from U.S. Department of Commerce (1981). This decision ensures that the variable of central interest, the ratio of the Gordon index to the NIPA index, does not vary drastically from 13.65 in 1947 to 5.13 in 1948 and to 10.75 in 1949, but is of tests in this subsection examine the effect of $\Delta RD/Y_{t-1}$ when Y, or real output, is measured using standard industry price deflators, as has been the case so far in the R&D literature. Subsection C.3. below conducts a parallel analysis in which the measure of real output is defined, alternatively, to reflect the quality change suggested by Gordon's deflators.

Table 2 reports results when equation (11) is estimated for the total sample of 792 observations, which consist of thirty-six annual observations for twenty-two assets. Line (1) shows that R&D has a 99 percent return through its effect on unmeasured quality change. Line (2) shows that this estimate is also quite high if time and industry dummies are included. The results in line (2), which allow for industry and time differences, are regarded as preferable.[12] The preferred estimate of the effect of R&D on unmeasured quality change is therefore 74 percent.

The average value of the independent variable, the change in the R&D stock divided by output, is .00855 within the total sample. Multiplying this average value by its coefficient from

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instead 11.43 for aircraft in 1948. Without such adjustments, these observations are substantial outliers.

[12] The hypothesis that the time dummies or the industry dummies, or the two jointly, are equal to zero can be rejected at the 95 percent level.

A specific dummy for the computer industry is not significant here, but one for the information technology industries is. The result in the total sample with time dummies is:

$$\dot{A}_G/A_G = \underset{(-.81)}{-.0010} + \underset{(4.69)}{1.018}\Delta RD/Y_{t-1} \underset{(-.73)}{-.009}COMP + \underset{(1.99)}{.016}IT \qquad \bar{r}^2=.118$$

t ratios

SEE = .059

Table 2

Increase in the Rate of Return to R&D Due to Unmeasured Quality Change. Pooled Data for Twenty-Two Assets, 1947-83.

Output (Y) is measured using existing deflators.

Line	Number of Observations	Constant	$\Delta RD/Y_{t-1}$	Dummies	r^2adj	SEE
(1)	792	.0126 (4.76)*	.990 (5.84)*		.040	.062
(2)	792	-.0096 -(.61)	.745 (3.16)*	Time and industry	.141	.059
(3)	778	.0119 (4.50)*	1.111 (6.35)*		.048	.062
(4)	778	-.0099 -(.62)	.866 (3.34)*	Time and industry	.154	.058

Source: Estimates of equation (11). Y is measured by standard deflators. Lines (3) and (4) omit computers from 1969-70 to 1982-83.

Table shows coefficients and t ratios.

* Indicates significantly greater than zero at the 95 percent level.

unmeasured quality change is essentially comparable, though slightly higher.[14]

C.2. Aggregation of Capital Using Service Prices.

The results in Table 2 above reduce productivity gains due to the Gordon drift by subtracting the increased amount of capital inputs. The increase in capital is calculated through the arithmetic aggregation of capital inputs. Most studies in the productivity literature aggregate capital inputs using service prices as weights. The service price method includes the capital composition effect, which measures the additional growth of capital inputs which occurs because of compositional shifts towards assets with high rental prices (mainly equipment). Unfortunately, it is difficult to measure service prices or the capital composition effect directly within Gordon's 22 capital goods industries. Information on property income is typically available for only a few years, so capital service prices cannot be based on actual income shares. Ex-ante rates of return, which are often adopted when property income is not available, are not plausible when issues of capital reevaluation are being considered; a constant ex-ante return, together with a different concept of capital, can imply quite different capital shares.

Nevertheless, because of the potential role of capital composition, it is necessary to allow for this effect in

[14] If computers are omitted entirely, the coefficient for $\Delta RD/Y_{t-1}$, with both time and industry dummies included, is .554 with a t ratio of 1.70.

determining the influence which the adoption of Gordon's deflators has on measures of productivity growth. We proceed by first establishing the existing capital composition effect in each two-digit industry using data from the Bureau of Labor Statistics multifactor productivity measurement program. Next, the capital composition effect is recalculated, in each of the same two-digit industries, using deflators, stocks, and capital service prices adapted to reflect Gordon's price drift. By comparing the two sets of estimates, we can determine how much faster capital grows, due to the composition effect, when the Gordon series replaces the standard data.

The composition effect is .45 percent a year greater than it normally is if a capital series based on the Gordon deflators is substituted for the standard data within the seven two-digit industries which produce equipment.[15] Since the property income share is approximately 12 percent, capital input growth changes of this magnitude have only a slight impact on productivity growth. We assign our (two-digit) estimates of the increase in capital input growth, due to composition, which occurs as a result of the adoption of the Gordon data, to every equipment asset included in each two-digit industry. When line (2) of

[15] As a standard of reference, in existing data for total manufacturing capital grew .73 percent a year more rapidly between 1949 and 1983 because of the capital composition effect. In the seven manufacturing industries considered here, the composition effect is .45 percent a year greater when it is calculated from the Gordon deflators. The implied increase in the composition effect, due to adoption of the Gordon deflators, is therefore about half as large as the usual influence of the composition effect.

Table 2 is reestimated, with the additional effect of the Gordon data on capital composition removed in this way, for each type of equipment in every year, the coefficient for R&D changes only slightly, from .745 to .749. Adjustment for capital composition clearly does not alter the central conclusions.

C.3. The Deflator Is Adjusted for the Gordon Price Drift.

The estimates reported in Table 2 have so far measured real output using conventional deflators, such as those typically available for each of the relevant industries. However, Gordon's work can also provide an alternative output price index, corrected for the quality measurement errors he describes. Estimates which adjust output prices further based on the Gordon deflator offer the advantage that the concept of output used in equation (11) fully reflects the unmeasured quality change which appears in the dependent variable of that equation. Table 3 repeats the analysis reported in Table 2 using such an alternative measurement of real output.

Table 3 shows that when Gordon's deflators are also used to adjust real output, the rate of return to R&D through the Gordon effect is somewhat higher. Line (2) of Table 3 shows that the preferred estimate of the effect of R&D on unmeasured quality change is .964. In the results which omit computers between 1969 and 1983 (line (4)), the effect of R&D on quality change is .902.

Table 3

The Effect of R&D on Unmeasured Quality Change.

Increase in the Rate of Return to R&D Due to Unmeasured Quality Change. Pooled Data for Twenty-Two Assets, 1947-83.

Output (Y) is measured using adjusted deflators, which reflect the quality changes documented by Gordon.

Line	Number of Observations	Constant	$\Delta RD/Y_{t-1}$	Dummies	r^2adj	SEE
(1)	792	.0136 (5.17)*	1.632 (5.16)*		.031	.062
(2)	792	-.0085 (-.54)	.964 (2.44)*	Time and Industry	.136	.059
(3)	778	.0136 (5.10)*	1.668 (5.25)*		.033	.062
(4)	778	-.0084 (-.52)	.938 (2.08)*	Time and Industry	.143	.059

Source: Estimates of equation (11). Lines (3) and (4) omit computers from 1969-70 to 1982-83. The values of real output (Y in equation (11)) are adjusted so that they also reflect the quality changes documented by Gordon.

Table shows coefficients and t ratios.

* Indicates significantly greater than zero at the 95 percent level.

The implied contribution of R&D to unmeasured quality change continues to be substantial when output is measured using the Gordon deflators. The mean value of the newly defined independent variable (the measure of R&D) in the full sample is .00454 which, when combined with the .964 coefficient from the central regression, implies an average .44 percentage point contribution to quality change, a considerable amount, though less than the .64 estimate obtained in Section C.1. A .44 contribution still represents more than 20 percent of the 2.18 percentage point (average) increase in multifactor productivity growth implied by Gordon's data.

When the Gordon deflators are used to determine the level of output, lagged output (Y_{t-1}) becomes very large for some of the high technology sectors. Consequently, $\Delta RD/Y_{t-1}$ becomes relatively small in these industries, particularly in later years. Since the measure of R&D input is growing less rapidly in such sectors, some evidence occasionally suggests that unmeasured quality change is growing faster in computers and IT than R&D growth would suggest.[16] However, the other conclusions reached

[16] For example, equation (c) in the medium-term results of Section C.2 becomes:

$$\dot{G}/G = \underset{(3.61)}{.0156} + \underset{(2.01)}{1.727}\Delta RD/Y_{t-1} + \underset{(2.13)}{.043}COMP + \underset{(1.47)}{.017}IT \quad \bar{r}^2 = .297 \quad \text{t ratios} \quad n = 66 \quad SEE = .025$$

Similarly, in the pooled annual data of Section C.3, when time dummies are included and other industry dummies are omitted, the summary result with the Gordon deflators used to define Y_{t-1} is:

$$\dot{A}_G/A_G = \underset{(-.56)}{-.0072} + \underset{(2.70)}{1.225}\Delta RD/Y_{t-1} + \underset{(.78)}{.010}COMP + \underset{(2.89)}{.022}IT \quad \bar{r}^2 = .144 \quad \text{t ratios} \quad n = 792$$

in this paper are not altered if the Gordon deflator is used to determine the level of output.

C.4. <u>The Direct Rate of Return to Research in Capital Goods</u>.

The direct return to research is customarily determined from equation (8). Information on A/A typically does not exist for these capital goods industries prior to 1958. However, the NBER Productivity Data Base does provide data on A/A between 1958 and 1983 for these industries.

Table 4 considers evidence on the direct return to research within these 1958-83 data. The results are somewhat ambiguous. Within the total sample, the effects of R&D on measured productivity growth are even negative; the results of line (1) are overwhelmingly dominated by a very large positive dummy for the computer industry. On the other hand, when computers are omitted for those years in which their output is defined by hedonic methods, in line (2), the effect of R&D on productivity is positive and very strong.

Typical estimates of the direct return to R&D are in the range of 30 percent (U.S. Bureau of Labor Statistics (1989)). In view of the divergence between lines (1) and (2), it is not possible to determine whether the direct return to R&D is unusually high in capital goods industries. Lines (3) and (4)

SEE = .060

Nevertheless, in most of the variants considered in this paper, computers and IT have no further effect beyond that of R&D.

Table 4

The Direct Effect of R&D on Multifactor Productivity Growth, with Conventional Measures of Output and with Alternative Measures of Output Based upon Gordon's Work.
Pooled Data for Twenty-Two Assets, 1958-83.

Direct returns to R&D, 1958-83.
1. Direct returns to R&D, using conventional measures of the residual.

Equation (8)

Line	Number of Observations	Constant	$\Delta RD/Y_{t-1}$	Dummies	r^2adj	SEE
(1)	550	.004 (.62)	-.317 (-1.76)	Time and Industry	.275	.041
(2)	536	-.001 (-.08)	1.142 (5.81)*	Time and Industry	.260	.035

Additional direct returns to R&D, 1958-83.
2. Additional direct returns to R&D, using measures of the residual adjusted for the quality change demonstrated by Gordon.

Equation (11)

Line	Number of Observations	Constant	$\Delta RD/Y_{t-1}$	Dummies	r^2adj	SEE
(3)	550	-.009 (-.58)	.729 (3.08)*	Time and Industry	.175	.054
(4)	536	-.009 (-.56)	.513 (1.72)*	Time and Industry	.205	.054

Table shows coefficients and t ratios.

* Indicates significantly greater than zero at the 95 percent level.

550 observations include each industry from 1958 to 1983. 536 observations exclude computers from 1969-70 to 1982-83.

show, for purposes of comparison, that the Gordon effect estimated for the full period also appears in the 1958-83 data.

Because the unmeasured technical change suggested by Gordon is so large, attention (Hulten (1992), Greenwood, Hercovitz and Krusell (1997)) has tended to concentrate on Gordon's measures as an index of the technical change in capital goods. Line (2) of Table 4 suggests that the direct returns to R&D may also be quite large in capital goods, so that the Gordon effect represents only one portion of the substantial overall technical change taking place in the production of capital.

C.5. Longer Lags.

R&D studies have frequently examined lags which are greater than the two years built into the R&D stocks analyzed here. Consequently, it is helpful to examine the potential effect of longer R&D lags. In our judgement, the R&D series used here, particularly in the change in the annual R&D stock version used throughout this paper, are not precise enough to support a detailed analysis of lags. Instead, in the spirit of equation (9), we examine the possibilty of longer lags by redefining research growth as the geometric mean of R&D growth in the current year (which already implies a two-year lag) and of R&D growth in each of the five preceeding years. Each of the six years involved is weighted equally. When R&D is redefined as average R&D growth over this two to seven year period, conclusions are essentially similar to those already reached above. For example, line (2) of Table 2 then becomes:

$$\dot{A}_G/A_G = \underset{(-.52)}{-.0082} + \underset{(3.72)}{1.187}\,\Delta RD/Y_{t-1} + \text{Time and Industry Dummies} \qquad \begin{array}{cc} r^2\text{adj} & \text{SEE} \\ .146 & .059 \end{array}$$

With two to seven year lags, the estimated effect of R&D is generally somewhat greater than with a two-year R&D lag.[17]

In summary, the evidence throughout Subsection C shows that the Gordon series on unmeasured quality change implies that there are very considerable additional returns to R&D in the capital goods sector. These additional returns imply a much greater economic role for R&D, which is sufficient to bring about a substantial reduction in the residual unexplained by other elements of production.

IV. Implications.

Nadiri (1993) reviewed the evidence on indirect returns to R&D and reported extremely high indirect and social rates of return, varying from 20% to over 100% with an average somewhere close to 50%. These are extremely high rates of return. Section IIIC showed that the Gordon effect, operating through unmeasured quality change in the capital goods sector, brings about similar

[17] If computers and information technology are introduced into this specification, instead of industry dummies, the result is:

$$\dot{A}_G/A_G = \underset{(-.88)}{-.011} + \underset{(5.45)}{1.504}\,\Delta RD/Y_{t-1} \underset{(-1.89)}{-.027}COMP + \underset{(1.18)}{.009}IT + \text{Time Dummies} \qquad \begin{array}{cc} r^2\text{adj} & \text{SEE} \\ .127 & .059 \end{array}$$

COMP and IT have no positive effect in this context.

increases in the direct return to R&D. Rates of return through this channel vary between 75% and 160%. These are also very high rates of return, even greater than those reported by Nadiri.

The correspondence between the high returns due to measurement error upstream and the high rates of return downstream certainly suggests that much of the downstream returns are due to measurement error. However, one cannot exclude the possibility that some of the downstream returns are due to genuine technology transfer rather than to measurement error.[18]

There has never been any real question that genuine technology transfer represents a real influence on production and productivity growth. On the other hand, if indirect R&D reflects only measurement error, analysts have felt (Gordon (1990), page 12) that such measurement error cannot make a real contribution in reducing the residual because of the Jorgenson critique.

The results in Section III have shown, however, that, even if all the indirect effects of R&D represent measurement error, the expanded direct effects of R&D are large enough that they can

[18] In actual practice, the distinction between errors in price measurement and genuine technology transfer can be somewhat murky. For example, computer or aircraft manufacturers typically work closely with their customers, adapting their products to customer needs, and showing potential customers how to use their products most effectively. This detailed interaction with customers would probably not appear in any realistic product specifications, no matter how detailed. Consequently, this sort of interaction could be seen as an error in price measurement, but it is at the same time also an example of genuine technology transfer.

cover all the observed downstream effect. Even if all the indirect effect is measurement error, this full amount can still be attributed to R&D upstream. If some portion of the indirect R&D effect instead represents real technology transfer, this too should clearly be credited to R&D. Consequently, all of the indirect R&D effect, whether it reflects measurement error or technology transfer, can be attributed to R&D, and thereby can help to reduce the residual.

Considerably more work than can be described here is necessary to nail down the empirical effect of indirect R&D. Stocks of indirect R&D must be prepared, the rate of return to indirect R&D must be determined, and the different channels through which indirect R&D affects productivity must be examined. Sveikauskas (a, forthcoming) carries out this further work. The results indicate that indirect R&D contributes .2 percent a year to long-term (1947-1987) productivity growth. This is a considerable sum which, for example, is greater than BLS estimates of the effect of direct R&D or of human capital (education and experience) over the corresponding period. Inclusion of this growth contribution also substantially increases the proportion of long-term economic growth which can be attributed to R&D.[19]

[19] In a sense, the estimates of the further direct returns to research, as obtained in Section III, are superior to customary estimates of the indirect returns to R&D because the estimates in Section III are obtained through a methodology in which output has already been explicitly adjusted for quality change. In many of the industries typically used to estimate the indirect returns to R&D, the indirect purchases of R&D are likely to be associated

In the calculations summarized above, the rate of return to indirect R&D is assumed to be 25 percent. This rate of return is intended to be conservative, and is selected on the basis of evidence from studies of individual innovations, such as Mansfield et al. (1977). Sveikauskas (a, forthcoming) discusses these issues in detail. If higher rates of return, such as those developed earlier in this paper, are used instead, the productivity contribution of indirect R&D is much greater. In either event, indirect R&D is an important contributor to productivity growth.

V. Conclusions.

The main point of this paper is that there is an appropriate conceptual framework and sufficient empirical evidence to conclude that indirect R&D is an important influence on multifactor productivity growth. Growth accounting should include indirect R&D as an element on the short list of factors, such as capital, human capital, and direct R&D, which determine growth in advanced industrial economies.

Since Jorgenson's (1966) important paper, economists have believed that quality change embodied in capital cannot be useful in explaining aggregate productivity growth. R&D is a channel through which unmeasured improvements in capital quality can once

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with unmeasured quality change, which is not captured in output prices. Further work is under way on this important topic.

again be important. Improvements in capital quality imply higher output growth in the capital goods sector, and this in turn implies a higher rate of return to R&D. R&D therefore makes more of a contribution to productivity growth, which reduces the residual. The increased returns to direct R&D, which occur when output in the capital goods sector is increased to reflect quality change, are very large and comparable to reported estimates of the indirect return to R&D.[20]

Measurement error is an important topic on which considerable further understanding is necessary. It is plausible that errors in measurement will be most important where production is dynamic and changing quickly. This study has shown that changes in the stock of R&D are important in bringing about the unmeasured quality change which Gordon (1990) has described in capital goods. These results support and expand upon prior evidence that the level of investment in R&D is associated with measurement error (Griliches and Lichtenberg (1989), Siegel (1994, 1997)).[21] The patterns reported here suggest that the growth of R&D stocks may provide a useful way of understanding the role which new

[20] Although Gordon's estimates of quality adjusted price deflators may in turn be subject to considerable measurement error, the fact that we find similar estimates of the rate of return to indirect R&D from an analysis of Gordon's data and from traditional methods (Sveikauskas, forthcoming, a) strengthens our confidence in both Gordon's work and in the traditional estimates.

[21] When R&D spending is increasing rapidly, as in the 1950's and 1960's, R&D expenditures may provide a useful approximation to the true increase in the R&D stock. However, once R&D is well established in the economy, as in the 1970's and 1980's, the increase in the R&D stock is a conceptually superior measure of technology.

products and product upgrading play in creating unmeasured quality change in prices over long periods of time. This issue has proven difficult to address empirically in data for any substantial portion of the economy.

Finally, some studies have indicated that computers and information technology add more to productivity than other types of assets do. The present paper offers somewhat mixed evidence on this issue. Much of the evidence suggests that R&D is the central underlying factor in such comparisons, and that unmeasured quality change in computers and information technology is no greater than the R&D contained in these assets would suggest.

Appendix I Data Issues.

This appendix describes the data used in this paper. Sveikauskas (b, forthcoming) provides a more complete description of the data, including the actual series used and many of the central intermediate steps used in preparing these data.

The measures of output, plant, equipment, inventories, materials, and labor inputs for 1958 to 1983 are obtained from the NBER Productivity Database. We use a version of the NBER data which describes industries according to the 1972 Standard Industrial Classification, and, as in Gordon's work, use 1972 as the base year. The NBER Database also contains information on materials, capital, and labor factor shares. The standard residual, $\dot{A}/A$, and measures of real output are calculated directly from this information.

For years prior to 1958, shipments and inventories are obtained from the Census or Annual Survey of Manufactures. Shipments deflators, which are used to convert shipments to real output, are obtained from the Department of Commerce. Plant and equipment are obtained from BLS Bulletin 2352, Outlook 2000.

Most of the industries included cover one or several three-digit industries. Output is the sum of the output from each relevant four-digit industry. This procedure is chosen because the information necessary for Divisia output aggregation across industries is not available for 1947-1958. Total capital is calculated as the sum of net stocks of plant, equipment, and inventories. Information on property shares, which could be used as the basis for Divisia aggregation of service prices, is available only for 1967, 1972, 1977, and 1982.

The use of direct, rather than Divisia, aggregation of output and capital is potentially a limitation. However, footnote 6 reports that the estimated effect of R&D is essentially the same over the 1958-83 period if a Divisia index of output is used instead of a constant dollar output index. Similarly, Section III.C.2 shows that Divisia aggregation of capital inputs does not change the central results much.

In order to determine the effect of the Gordon changes on multifactor productivity it is necessary to allow for the effect of increases in materials or capital input. Unfortunately, detailed information on the factor shares of specific materials or of property income in a given industry is typically available only for a few input-output years. In order to overcome this data limitation, we shall utilize 1972 factor shares to apprximate the corresponding factor shares in every year between 1947 and 1983. For example, $(\alpha_k)_i$, the share of capital in industry i, in equation (3) can be approximated by $(\alpha_k)_{i72}$, the 1972 share of property income given in Ritz, Roberts, and Young (1979). Similarly, α_{mhi}, the share of materials h in the production of asset i, can be approximated by estimates of this share from the detailed input-output table for 1972.

Given this assumption concerning factor shares, it is an easy matter to calculate the effect of increased materials and capital input on productivity growth in each industry. For example, the effect of an increase in the quality of materials purchases from one's own industry is:

$$\alpha_{mii72} \ (\dot{G}/G)_{ij}$$

where α_{mii72} is the share of materials i in industry i in the year 1972 and $(\dot{G}/G)_{ij}$ is Gordon's improvement in the quality of output for industry i in year j. Given that the relevant factor share is the same in each year, as assumed, this procedure can be used, together with information on $(\dot{G}/G)_{ij}$, to determine the effect of improvements in the materials purchased from one's own sector for each asset i in every year j.

Similarly, the effect of improvements in materials purchases from the other capital goods sectors can be allowed for by the expression:

$$\sum_{c=1}^{21} (\alpha_{mci72}) \ (\dot{G}/G)_{cj}$$

where (α_{mci72}) is the share of materials c in industry i in 1972. $(\dot{G}/G)_{cj}$ is Gordon's index of unmeasured quality change in industry c in year j. For each industry, this summation calculates the increase in materials purchases from the other 21 industries which produce capital assets. The summation is conducted across the other 21 industries, but excludes the effect of materials purchased from one's own industry, which has already been dealt with in the preceeding discussion.

It is slightly more difficult to correct the equipment stocks to allow for Gordon's quality change. The percentage change in the capital stock can be calculated as $\Delta(S + E + I)/(S + E + I)$, where S is the stock of structures, E is the stock of equipment, and I is the stock of inventories. The effect on productivity growth in industry i in year j is then:

$$(\alpha_k)_{i72} \quad (\Delta(S + E + I)/(S + E + I))_{ij} \qquad \text{(a)}$$

We have recalculated the equipment stocks, including separate stocks for each type of capital equipment, in each industry. A new stock of equipment, E_G, is calculated based on the new Gordon deflators for each asset. E_G is the sum of the new capital stocks calculated for each type of asset based upon Gordon's deflators. The new implied effect of capital on productivity is:

$$(\alpha_k)_{i72} \quad (\Delta(S + E_G + I)/(S + E_G + I))_{ij} \qquad \text{(b)}$$

and expression (b) less expression (a) shows the extent to which the revaluation of capital reduces productivity growth and the impact of $(\dot{G}/G)_{ij}$ on $(\dot{A}/A)_{ij}$.[22]

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22 We do not have the actual investment series which are the basis for E in the NBER Productivity Database, so in practice we prepare estimates of E_G and E from a closely related investment

In all calculations, the Gordon price index is set equal to the official index in 1947, but increases more slowly thereafter to reflect the unmeasured quality change demonstrated by Gordon.

Appendix II <u>Alternative Theoretical Frameworks</u>.

Most studies have examined the return to indirect R&D within information on the growth of gross output within different industries, and so our framework is expressed in such terms. However, it has been suggested that the analysis should examine the level, rather than the growth, of output or should concentrate on gross output in only the downstream industry.

If equation (1) of the text, in level form, is inserted into equation (2), also in level form, the result is:

$$Y^d = (L^d)^{\alpha_L} (L^u)^{\alpha_L \alpha_U} (M^d)^{\alpha_M} (M^u)^{\alpha_M \alpha_U} (R^u)^{\alpha_R \alpha_U} (\theta^u)^{\alpha_U} \theta^d \quad \text{(i)}$$

In (i) the effect of research is $(R^u)^{\alpha_R \alpha_U}$ and the residual is $(\theta^u)^{\alpha_U} \theta^d$.

Now consider the effect of measurement error which increases the upstream residual and decreases the downstream residual, as in equations (3) and (4) of the main text. If the upstream residual increases from θ^u to $\theta^u g$ $(g > 1)$, the contribution of the upstream residual in (i) increases to $(\theta^u)^{\alpha_U} g^{\alpha_U}$. Since output and the inputs are unaltered in (i), the downstream residual must correspondingly decrease to $\theta^d g^{-\alpha_U}$. There is no change in the overall residual. (i) becomes:

$$Y^d = (L^d)^{\alpha_L} (L^u)^{\alpha_L \alpha_U} (M^d)^{\alpha_M} (M^u)^{\alpha_M \alpha_U} (R^u)^{\alpha_R \alpha_U}$$

$$(\theta^u)^{\alpha_U} g^{\alpha_U} \quad \theta^d g^{-\alpha_U} \quad \text{(ii)}$$

Now assume there is again an increase in upstream output due to measurement error, but this time the added output is attributed to upstream research, as in equations (5) through (7) of the text. The upstream research effect therefore increases from $(R^u)^{\alpha_R}$ to $(R^u)^{\alpha_R + b}$. In contrast, the upstream residual is unchanged, since all the increased upstream output is due to research. Expression (i) then becomes:

$$Y^d = (L^d)^{\alpha_L} (L^u)^{\alpha_L \alpha_U} (M^d)^{\alpha_M} (M^u)^{\alpha_M \alpha_U} (R^u)^{\alpha_R \alpha_U + b\alpha_U}$$

$$(\theta^u)^{\alpha_U} \quad \theta^d (R^u)^{-b\alpha_U} \quad \text{(iii)}$$

where the downstream residual must be reduced to reflect the increased upstream return to R&D.

Regardless of which particular framework is adopted, if an increase in the upstream residual is accompanied by a corresponding decrease in the downstream residual, there is no net change in overall productivity. On the other hand, if (part of) the increased upstream output is attributed to R&D, which this paper argues is theoretically and empirically plausible, more of output is assigned to R&D and the residual not elsewhere explained decreases.

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series, and apply the ratio E_G/E to the value of E in the NBER Data Bank.

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