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# Errors of Measurement and the Recent Acceleration in Manufacturing Productivity Growth

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*Abstract*

Using detailed (4-digit SIC) industry data for the years 1958–1989, I examine whether the recent acceleration in manufacturing productivity can be attributed to the effects of mismeasurement of the prices of inputs and output, by testing a model linking a set of proxy variables for measurement error to a series of measures of acceleration in total factor productivity (TFP). Alternative TFP estimates are presented in order to determine if the findings are sensitive to the method of TFP calculation. The results are inconsistent with the measurement error hypothesis and invariant to the specification of the TFP equation.

## 1. Introduction

The recent recovery in measured manufacturing productivity growth has been quite strong. Aggregate statistics show that average growth in total factor productivity (TFP) between 1980 and 1989 was 2.9%, higher even than the productivity gains reported during the years before the productivity slowdown began in the 1970s.[1] The improvement in economic performance was even more striking at the end of the decade, with an average annual TFP growth rate of 4.6% between 1985 and 1989.[2] Some [Denison (1989), Mishel (1988)] have argued that the magnitude of this revival has been overstated due to a systematic downward bias in measures of input growth. Among the factors that are alleged to have exacerbated measurement error in conventional TFP estimates are increases in the rate of foreign and domestic outsourcing of materials and services and an expansion in the rate of investment in computers. Real output and labor input may also be mismeasured because of the new goods problem and changes in the quality of the labor force. The purpose of this paper is to assess whether the recent acceleration in manufacturing productivity growth can be attributed to these errors of measurement.

This study builds on previous work [Siegel-Griliches (1992)] in which we used detailed (4-digit SIC) industry data to determine whether the improvement in economic performance was related to the mismeasurement of capital, materials, and service sector inputs. I extend this investigation into the effects of measurement error on estimates of productivity growth in four ways: First, I use a wide variety of methods to compute estimates of TFP, based on data that are ideally constructed for these calculations. This allows me to assess whether reported productivity trends are consistent across different methods of TFP calculation. Second, I estimate a regression model of measurement error and determine whether the empirical results are sensitive to different methods of TFP calculation. Third, I include controls for the effects of errors in the measurement of output, labor, and materials inputs. Finally, I analyze more recent and more comprehensive data on productivity, outsourcing, and computer investment from the 1987 and 1989 economic censuses and other sources.

The next section of the paper describes potential sources of measurement error of output and inputs. Section 3 presents the methodologies used to calculate TFP estimates. Section 4 describes the econometric model that links proxies for measurement error to the productivity estimates. Section 5 contains empirical findings. Conclusions and suggestions for additional research are discussed in the final section of the paper. A data appendix is also included.

## 2. Potential Sources of Measurement Error of Real Output and Input Growth

Conventional measures of TFP are based on the assumption that the prices of all factor inputs and output are measured without error. In this study, we allow for the possibility that the price deflators of output, capital, labor, materials, and purchased services are measured with error.[3] A summary of potential sources of price mismeasurement is contained in Table 1.

This table indicates that most of the mismeasurements are likely to lead to the simultaneous understatement of output and input growth rates. That is, an increase in the rate of innovative activity could lead to understatement of the growth in real output, but also of capital, materials, and labor input. It follows that the overall impact on measured TFP growth will depend on the relative magnitudes of such errors and the cost shares of the mismeasured inputs. Thus, we cannot make a definitive statement about the *direction of bias* in a measure of TFP growth, and the consequences of these errors becomes strictly an empirical issue. Before assessing the global impact of mismeasurement, we discuss the sources of measurement error.

*Table 1.* Measurement errors concerns in the estimation of productivity (trends to be investigated). $Q = F(K, L, M, S)$ or $C = G(P_k, P_l, P_m, P_s, Q)$

| Variable | Potential Source of Mismeasurement | Potential Bias |
|---|---|---|
| output | new products generated by the industry | underestimation of real output |
| capital | industry's investment in computers | underestimation of capital input |
| labor | changes in the quality of the labor force | unclear |
| materials | foreign outsourcing of materials | underestimation of materials input |
| materials | investment in computers undertaken by suppliers of materials input | underestimation of materials input |
| services | outsourcing and/or increased use of purchased services | underestimation of service input |

### 2.1. Price of Output

The major concern in output price measurement is adjustment to reflect changes in product quality. If the characteristics of goods are changing over time, and these changes are not fully incorporated in the industry price series, mismeasurement will arise.[4] For this study, we are interested in the time series and cross sectional (across industries) variation in the quality adjustments (hence, errors in output deflators) because the productivity estimates are calculated at the detailed industry level. I postulate that the growth rate of the output deflator ($P_{qi}$) in industry $i$ is measured with error:[5]

$$\dot{P}_{qi} = \dot{P}^*_{qi} + \epsilon_{pq} \tag{1}$$

where the $\cdot$ and $*$ superscripts denote the observed and true growth rates, respectively. Our maintained assumption is that the error in the industry output price deflator ($\epsilon_{pq}$) is proportional to the rate of introduction of new products generated by the industry:

$$\epsilon_{pq} = \beta_Q \text{NEWPROD}_i \tag{2}$$

The use of new products as a proxy for price mismeasurement is consistent with Triplett (1988) and Diewert's (1992) contention that a *new goods* bias constitutes a major source of error in output deflators.[6]

As summarized in Triplett (1988), new goods can introduce bias in price measures in two ways: First, price data on new goods are usually not collected until the product has been on the market for several years and producers have generated substantial revenues. Price movements that occur between the time the product has been introduced and its appearance in the price statistics are not incorporated in the price index.[7] In a recent audit of the Producer Price Index (PPI) for prescription drugs, Berndt, Griliches, and Rosett (1992) found that products less than two years old were not included in the sample used to construct the PPI. A second source of bias stems from the fact that unmeasured changes in quality are likely to be greater for new products than for existing products. This follows from the hypothesis that the characteristics and quality dimensions of new goods change more rapidly than those of existing goods.[8]

Table 2 presents descriptive statistics on new products created within 4-digit SIC industries over two five year periods, 1972–1977 and 1977–1982, based on data from quinquennial Manufacturing Censuses in 1972, 1977, and 1982. As an additional measure of the economic significance of new products (not shown on Table 2), I have calculated the percentage of industry revenue in 1977 and 1982 that was derived from new products. The media value of this variable increased from 4.8% in 1977 to 6.4% in 1982, indicating that new goods constituted about 5% of output over the sample period.[9] These figures indicate that new products (or new product categories) constitute a non-negligible, though relatively constant proportion of manufacturing output.

*Table 2.* Descriptive statistics on measurement error proxies: Output, capital, materials, and services ($N$ = 450 manufacturing industries).

| Proxy for Mismeasurement of Output Price | Mean | Median | Minimum | Maximum |
|---|---|---|---|---|
| (1) % of new products created between 1972 and 1977 (new products as a % of existing products) | 17.8 | 2.8 | 0 | 100 |
| (2) % of new products created between 1977 and 1982 (new products as a % of existing products) | 20.2 | 9.5 | 0 | 100 |
| **Proxy for Mismeasurement of Capital Price** | **Mean** | **Median** | **Minimum** | **Maximum** |
| (1) % of new captial expenditures devoted to computers—1977 | 2.3 | 1.3 | 0.0 | 24.3 |
| (2) % of new capital expenditures devoted to computers—1982 | 4.0 | 2.6 | 0.0 | 36.5 |
| (3) % of new capital expenditures devoted to computers—1987 | 9.0 | 6.1 | 0.0 | 93.9 |
| **Proxies for Mismeasurement of Materials Price** | **Mean** | **Median** | **Minimum** | **Maximum** |
| (4) % of foreign materials 1977* | 3.8 | 3.4 | 0 | 42.1 |
| (5) % of foreign materials 1982* | 4.8 | 3.8 | 0 | 47.0 |
| (6) % of foreign materials 1987 | 7.8 | 5.4 | 0 | 72.6 |
| (7) # of industries supplying materials to a given manufacturing industry—1987 | 20.8 | 18.0 | 1.0 | 56.0 |
| (9) % of new capital expenditures devoted to computers by an industry's suppliers—1982 | 0.7 | 0.5 | 0.0 | 5.4 |
| (10) % of new capital expenditures devoted to computers by an industry's suppliers—1987 | 2.6 | 1.9 | 0.0 | 45.4 |
| **Proxies for Mismeasurement of Service Price** | **Mean** | **Median** | **Minimum** | **Maximum** |
| (1) Selected purchased services/industry output—1977 (in %) | 1.08 | 0.93 | 0.10 | 5.79 |
| (2) Selected purchased services/industry output—1982 (in %) | 1.05 | 0.87 | 0.12 | 9.45 |
| (3) Selected purchased services/industry output—1987 | 1.04 | 0.78 | 0.08 | 8.76 |
| (5) Central office employment/production employment—1977 (in %) | 6.09 | 4.47 | 0.05 | 44.5 |
| (6) Central office employment/production employment—1982 (in %) | 7.28 | 5.56 | 1.07 | 50.1 |
| (7) Central office employment/production employment—1987 (in %) | 7.10 | 6.00 | 1.25 | 34.6 |

Sources — Output: Author's calculations based on U.S. Census of Manufactures 1972, 1977, 1982, and 1987.
Capital: NBER Productivity File—based on U.S. Census and Annual Surveys of Manufactures 1959-1989.
Materials: BEA Input Output Tables 1977, 1982—*Values for 1977 and 1982 are imputed measures based on methodology described in Siegel-Griliches (1991).
Services: U.S. Censuses of Manufactures and Auxiliary Establishments 1977, 1982, and 1987.

## 2.2. *Price of Capital*

The growth rate of the price of capital is assumed to be mismeasured:

$$\dot{P}_{ki} = \dot{P}^*_{ki} + \epsilon_{pkt} \tag{3}$$

where $P_{ki}$ is the capital stock deflator and $\epsilon_{pkt}$ is a moving average of investment deflator errors, with weighted depreciated (surviving) values of the respective net investments. Our maintained assumption is that the error in the capital stock deflator ($\epsilon_{pk}$) is proportional to the industry's rate of investment in computers:[10]

$$\epsilon_{pk} = \beta_K \mathrm{COMPINV}_i \tag{4}$$

where $\mathrm{COMPINV}_i$ = the fraction of industry $i$'s capital expenditures that is devoted to computers. The use of this proxy is supported by the fact that computers, more than other capital goods, have experienced rapid technological change and significant improvements in quality. Capital goods deflators that are used in most industry productivity studies do not even include hedonic adjustments for quality changes in computers. Before these adjustments were made, the price of computers was assumed to be relatively constant over time. As reported in Baily and Gordon (1988), the BEA hedonic, or quality-adjusted, price indexes for computers indicate an average annual percentage decline of approximately 20% in the computer price index for the years 1972–1987. Recent evidence indicates that even hedonic prices may understate true price changes since they are based on mainframe computers. Berndt and Griliches (1990) report even larger price declines for microcomputers.

To summarize, we contend that existing capital goods deflators overstate the true price of computers, leading to underestimation of the industry capital stock. The extent of the mismeasurement depends, of course, on the share of new investment devoted to computers and the ratio of capital to industry output or capital intensity.

Table 2 shows a substantial increase in the rate of investment in computers. For the representative manufacturing industry, the percentage of capital expenditures devoted to computers has virtually doubled over each five-year period. The mean value of this variable increased from 2.3% in 1977 to 4.0% in 1982, and increased again to 9.0% in 1987. Between 1982 and 1987, the average increase in this proportion was approximately five percentage points. Only 72 (out of 450) industries reported a lower percentage in 1987 than in 1982.[11] We also find that the average capital intensity (not shown on the table) increased by ten percentage points over the sample period.[12]

## 2.3. *Price of Materials*

Errors of measurement of materials prices are also considered. They are assumed to arise from two sources. First, investments in computers undertaken by an industry's suppliers of materials could improve the quality of materials. If there are incomplete adjustments for these changes in quality (as we contend throughout the paper), the true price of materials may be lower than the actual materials deflator. Thus, as discussed in Griliches and

Lichtenberg (1984b), errors in output deflators lead to errors in materials prices, since the latter series is also based on output prices.[11]

A second possible source of measurement error is outsourcing of materials to foreign establishments. For example, changes in relative factor prices, due to currency fluctuations or other factors, may induce domestic plants to purchase materials from foreign plants. Thus, the domestic price of materials may be substantially different from the price of imported materials. The potential for mismeasurement arises because the producer price index (PPI), which is used to deflate materials input, is based on domestic prices only. These factors may induce errors in the growth rate of the materials price deflator:

$$\dot{P}_{mi} = \dot{P}^*_{mi} + \epsilon_{pm} \tag{5}$$

where $P_{mi}$ is the materials price deflator in industry $i$. Our maintained assumption is that the error in the materials price, $\epsilon_{pm}$, is proportional to the extent to which investments in computers are embodied in purchased inputs (the rate of investment in computers by suppliers of materials inputs) and to the usage of foreign materials in production:

$$\epsilon_{pmi} = \beta_{m1}\text{SUPPCOMP}_i + \beta_{m2}\text{FORMAT}_i \tag{6}$$

where

$\text{SUPPCOMP}_i = \Sigma_j(VQ_{ji}/VQ_j)(C_j/CE_j)$

$VQ_{ji}/VQ_j$ = the fraction of supplying industry $j$'s output that is sold to industry $i$ as an input.

$(C_j/CE_j)$ = the fraction of the supplying industry $j$'s capital expenditures that was spent on computers.

$\text{FORMAT}_i$ = the percentage of foreign materials used by industry $i$.[14]

Analysis of interindustry transactions and investment patterns of suppliers has been used to test for the existence of spillovers in research and development. Scherer (1982) found that R&D investments embodied in purchased inputs had a stronger impct on an industry's productivity growth than its own R&D investments.[15] Caballero and Lyons (1989, 1990) also find evidence of externalities in U.S. manufacturing industries.[16]

Table 2 contains statistics on the use of foreign inputs and estimates of investments in computers embodied in materials inputs. Purchased materials constitute, on average, approximately 50% of input cost. Thus, mismeasurement of materials prices could have a large impact on measures of productivity or value added. The use of foreign or imported inputs has also increased over time, especially between 1982 and 1987. In 1987, the average industry purchased inputs from 21 other sectors (12 within manufacturing). The table also contains estimates of SUPPCOMP, which I calculate as the percentage of new capital expenditures devoted to computers by an industry's suppliers. Our evidence implies that this spillover measure increased substantially from 1982 to 1987.[17]

*2.4. Price of Services*

Service sector inputs in manufacturing consist of purchased services and services that are provided to manufacturing plants by central office establishments.[18] There is a strong consensus among economists [see Griliches (1992)] that service sector prices are not well measured, due to difficulties in adjusting the output of these industries for changes in product quality. Thus, the growth rate of the price deflator for services is assumed to be measured with error:

$$\dot{P}_{si} = \dot{P}^*_{si} + \epsilon_{ps} \tag{7}$$

Our maintained assumption is that measurement error in the price of services is proportional to the demand for selected purchased services (SELSERV) and the ratio of central office to production employment (RATCAO):[19]

$$\epsilon_{ps} = \beta_{s1}\text{SELSERV}_i + \beta_{s2}\text{RATCAO}_i \tag{8}$$

These variables are selected as proxies because they constitute the best available data on the volume of services used by manufacturing plants. We do not observe any indicators of changes in the quality of these services, which is unfortunate since we have argued that prices are mismeasured because of inadequate adjustments for quality changes. Instead, we assume that the magnitude of these errors is related to the volume of services used in the production process.

Table 2 presents data on selected purchased services and central office staff. These figures indicate that the use of purchased services remained roughly constant over the sample period. In fact, there was a small decline in the mean and median values of the factor share for services. There was a small increase in the median value of the ratio of central office to production employment, signifying an increase in the provision of intra-firm services.[20]

*2.5. Price of Labor*

The source of error in the price of labor input is unmeasured changes in the quality of hours. Thus, the growth of the average wage (or hours) is assumed to be measured with error:

$$\dot{P}_{li} = \dot{P}^*_{li} + \epsilon_{pl} \tag{9}$$

where $P_{li}$ is the average wage or price of labor in industry $i$. The error in the labor input price deflator ($\epsilon_{pl}$) is hypothesized to be proportional to the change in an index of the industry's labor quality:

$$\epsilon_{pl} = \beta_L\text{QUALIND}_i \tag{10}$$

Indexes of labor quality are derived from estimates of changes in the composition of the workforce, which are assumed to be correlated with quality change.[21] Several studies of aggregate economic growth [Denison (1962), Jorgenson, Gollop, and Fraumeni (1987), and Dean, Kunze, and Rosenblum (1988)] have included labor quality adjustments.

The theoretical framework used to construct estimates of labor quality is taken from Chinloy (1980). A measure of labor input ($l$) is expressed as a function ($G$) of hours ($h$) worked by $i$ types of workers in year $t$:

$$l_t = G(h_{1t}, h_{2t}, \ldots, h_{it}) \tag{11}$$

If $G$ is a linearly homogeneous function and the market for labor is perfectly competitive, we have:

$$\begin{aligned} \frac{\partial ln\ l_t}{\partial t} &= \Sigma_i v_{it} * \frac{\partial ln\ h_{it}}{\partial t} \\ &= \Sigma_i (w_{it}h_{it}/\Sigma_i w_{it}h_{it}) * \left(\frac{\partial ln\ h_{it}}{\partial t}\right) \end{aligned} \tag{12}$$

where $v_{it}$ is the share of total compensation paid to the $i$th type of labor, $w$ is the hourly wage, and $wh$ is hourly compensation. Chinloy (1980) defines labor quality per hour and its growth rate as:

$$a_t = l_t/\Sigma_i h_{it} = l_t/m_t \tag{13}$$

$$\frac{\partial ln\ a_t}{\partial t} = \Sigma_i (v_{it} - b_{it}) * \frac{\partial ln\ h_{it}}{\partial t} \tag{14}$$

where $b_{it} = h_{it}/m_t$, the share of total hours worked devoted to the $i$th labor type. Thus, the growth in the quality of labor input is a weighted sum of growth rates of hours worked by each type of labor, with weights equal to the difference between the shares in compensation and hours, respectively.

It is common in studies of this type [see Jorgenson, Gollop, and Fraumeni (1987) and Dean, Kunze, and Rosenblum (1988)] to assume that $G$ is a translog function and that the parameters of this function are symmetric. This yields the following expression for the growth rates of a translog index of labor input and hours in discrete time:

$$d_t = \Sigma_i 1/2(v_{it} + v_{i,t-1}) * (ln\ h_{it} - ln\ h_{i,t-1}) \tag{15}$$

$$h_t = ln\ m_t - ln\ m_{t-1} \tag{16}$$

A discrete approximation for the growth rate in quality (equation (14)) can be expressed as:

$$\begin{aligned} \text{QUALIND}_t &= q_t = d_t - h_t \\ &= \Sigma_i 1/2(v_{it} + v_{i,t-1}) * (ln\ h_{it} - ln\ h_{i,t-}) - (ln\ m_t - ln\ m_{t-1}).^{22} \end{aligned} \tag{17}$$

Based on estimation of equation (17), we have calculated estimates of the average annual percentage growth in the quality of production and nonproduction labor in 21 manufacturing industries during two periods, 1973–1979 and 1979–1989.[23] These figures are presented in Table 3. In general, we do not observe extreme movements in these variables within periods, except in tobacco, apparel, instruments, lumber, leather, and stone, glass, and clay industries. Across periods, there is little evidence of a strong trend, given that the change in growth rates is positive in 12 out of 21 industries.

In this section, we have outlined a series of proxies for measurement error. In Section 3, we will present a model that tests whether these proxies explain movements in productivity. In the next section of the paper, we describe a variety of procedures that are used to develop alternative estimates of productivity growth.

*Table 3.* Labor quality indexes for nonproduction and production employees in manufacturing industries.

| | | Production Workers | | | Nonproduction Workers | | |
|---|---|---|---|---|---|---|---|
| SIC | Industry Name | Average Annual Growth in Quality Index 73–79 (1) | Average Annual Growth in Quality Index 79–89 (2) | Acceleration in Quality Index (2)–(1) | Average Annual Growth in Quality Index 73–79 (3) | Average Annual Growth in Quality Index 79–89 (4) | Acceleration in Quality Index (4)–(3) |
| 20 | Food | −0.4 | −0.5 | 0.9 | −0.0 | −0.1 | −0.1 |
| 21 | Tobacco | −1.8 | −2.8 | −1.0 | −1.1 | −0.7 | 0.4 |
| 22 | Textiles | 1.2 | 0.3 | −1.0 | 0.0 | −0.1 | −0.2 |
| 23 | Apparel | −1.7 | 0.3 | 2.1 | −0.0 | 0.0 | 0.0 |
| 24 | Lumber | 0.8 | −2.6 | −3.4 | −0.0 | 0.1 | 0.2 |
| 25 | Furniture | 0.6 | −0.8 | −1.4 | −0.2 | −0.1 | 0.1 |
| 26 | Paper | −0.7 | −0.8 | −0.1 | −0.1 | −0.0 | 0.1 |
| 27 | Printing | −0.2 | 0.3 | 0.5 | −0.1 | −0.1 | 0.0 |
| 28 | Chemicals | 0.4 | 0.3 | −0.1 | −0.2 | −0.0 | 0.1 |
| 29 | Petroleum | 0.4 | 0.5 | 0.0 | 0.3 | −0.3 | −0.6 |
| 30 | Rubber | −1.5 | −0.8 | 0.6 | 0.1 | −0.2 | −0.3 |
| 31 | Leather | −7.3 | −2.7 | 4.7 | −0.3 | −0.2 | −0.1 |
| 32 | Stone, Clay, Glass | −1.4 | 0.1 | 1.5 | −0.0 | −0.2 | −0.2 |
| 33 | Primary Metals | 0.7 | −0.2 | −1.0 | −0.0 | −0.1 | −0.1 |
| 34 | Fabricated Metals | −0.8 | 0.4 | 1.2 | −0.2 | −0.1 | 0.1 |
| 35 | Nonelectric Machinery | −0.3 | 0.2 | 0.4 | −0.1 | −0.0 | 0.0 |
| 36 | Electric Machinery | −0.9 | −0.2 | 0.6 | −0.1 | −0.1 | −0.0 |
| 38 | Instruments | −0.9 | 0.2 | 1.0 | −0.3 | 0.6 | 0.9 |
| 39 | Miscellaneous Manufacturing | −0.3 | 0.5 | 0.8 | −0.4 | −0.1 | 0.3 |
| 3711 | Motor Vehicles and Equipment | 0.0 | −0.1 | −0.2 | −0.0 | −0.2 | −0.1 |
| 372 | Other Transportation Equipment | 0.1 | −0.2 | −0.3 | 0.1 | −0.0 | −0.1 |

## 3. Measurement of Total Factor Productivity Growth

The conventional method used to calculate productivity growth ($\dot{TFP}_t$) is to construct estimates of real output growth minus a weighted average of the rates of growth of real inputs, with factor shares as weights, sometimes referred to as the *Solow residual*. Jorgenson and Griliches (1967) showed that an equivalent measure of TFP is the rate of growth of the price of output ($P_q$) minus a share-weighted average of changes in input prices ($P_i$):

$$\dot{TFP}_t = \sum_{i=1}^{4} S_{it}\dot{P}_{it} - \dot{P}_{qt} \tag{18}$$

where $S_{it}$ = Average Share of factor $i$ in the total cost at time $t$, factors $i = K, L, E$, and $M$ and $i$ again indexes the factor inputs.

We can also calculate TFP growth and concomitant effects of measurement error in factor prices without imposing the rather strong maintained assumption of profit maximization associated with the Solow residual. If we assume only cost minimization, we can derive other discrete, implicit measures of TFP. As shown by Diewert (1976), if the technology is linearly homogeneous and Hicks neutral, a change in TFP can be constructed from estimates of changes in a cost function:

$$c(p_t, Q_t, t)/c(p_0, Q_0, 0) = Q_t c(p_t)A(0)/Q_0 c(p_0)A(t) \tag{19}$$

or

$$A(0)/A(t) = TC_t Q_0 c(p_0)/TC_0 Q_t c(p_t) \tag{20}$$

where 0 is the base period, $t$ is the time period over which technical change is to be evaluated, $TC$ is the reported total cost, and $p$ is a vector of factor prices. The left hand side of equation (20) represents the reciprocal of a technical change index (the state of technology evaluated at two different points in time).

To estimate these indexes, it is necessary that we specify a functional form for the cost function. Recent empirical work [see Morrison (1988)] has focused on flexible functional forms, such as the translog, and generalized Leontief functions. These functional forms allow both the elasticities of substitution and scale to vary with output and/or factor proportions. The translog average cost function has the following form:

$$lnC = \alpha_0 + \Sigma_i \alpha_i lnp_i + 1/2\Sigma_i\Sigma_j\beta_{ij} lnp_i lnp_j \tag{21}$$

Diewert (1976) shows that the technical change index corresponding to the translog is:

$$A(0)/A(t) = (TC_t Q_0/TC_0 Q_t) * \{\Pi_i (p_t^0/p_i^t)^{(1/2(s_{i0}+s_{it})}\} \tag{22}$$

An alternative functional form for ($c$) is the Generalized Leontief Average Cost function, developed by Diewert and Wales (1987):

$$C = \Sigma_i\Sigma_j \beta_{ij}(p_i)^{1/2}(p_j)^{1/2} \tag{23}$$

The technical change index associated with the Generalized Leontief cost function is:

$$A(0)/A(t) = (Q_t/Q_0) * \frac{1 - 0.5\Sigma_i \frac{s_{it}(p_{it} - p_{i0})}{p_{it}}}{1 + 0.5\Sigma_i \frac{s_{i0}(p_{it} - p_{i0})}{p_{i0}}} \quad (24)$$

For completeness, we present the TFP indexes corresponding to the translog and Generalized Leontief production functions. For the translog case, we have:

$$A(t)/A(0) = (Q_t/Q_0)\Pi_i(X_{i0}/X_{it})^{(1/2)(s_{it}+s_{i0})} \quad (25)$$

where the $X$ refers to the deflated values of the inputs. For the Generalized Leontief case, we have:

$$A(t)/A(0) = \frac{1 - 0.5\Sigma_i \frac{s_{it}(Q_{it} - Q_{i0})}{Q_{it}}}{1 + 0.5\Sigma_i \frac{s_{i0}(Q_{it} - Q_{i0})}{Q_{i0}}} \quad (26)$$

Note that as in the case of the Solow residual, the index number framework allows us to construct measures of TFP using observable data on factor shares and factor prices.

We can also measure TFP growth based on econometric estimation of the cost function. Ohta (1975) has shown that the dual (cost function based) rate of total factor productivity growth can be expressed as:

$$\dot{\mathrm{TFP}}_t = -[1/((\partial lnC)/(\partial lnQ))][\partial lnC/\partial t] \quad (27)$$

Econometric estimation obviates the need to use factor shares (which may also be measured with error) and serves as a useful test of the consistency of the index number results. Another useful feature of the econometric approach is that we do not need to impose constant returns to scale and Hicks neutral technical change.

An additional problem with the measures of TFP growth that we have outlined in this section is that they are based on a full static equilibrium specification. TFP growth can also be estimated using a dynamic cost function framework, described in Morrison (1990), which allows for the quasi-fixity of capital and incorporates the effects of adjustment costs of capital. This approach also allows for the construction of TFP estimates that are adjusted for fluctuations in capacity utilization.

The methodology used to calculate the econometric estimates of TFP is describes as follows: A variable cost function $G$ is specified, from which we derive optimal factor demand equations:

$$G = G(P_i, K, \Delta K, Q, t) \quad (28)$$

where the $i$ subscript refers to the prices of the four variable factors, nonproduction labor ($L1$), production labor ($L2$), energy ($E$), and materials ($M$). Capital ($K$) is a quasi-fixed factor and $\Delta K$, net capital investment, represents internal adjustment costs. The following Generalized Leontief restricted cost function [see Morrison (1988)] is characterized by

i. zero marginal adjustment costs at a steady state,
ii. separability between the quasi-fixed factor (capital) and its adjustment cost,
iii. nonconstant returns to scale, and
iv. nonneutral technical change.

Imposing i. and ii. and symmetry of parameters ($\beta_{ij} = \beta_{ji}$ for all $i, j$) yields the following expression for the variable cost function:

$$VC \equiv G = Q * \{\Sigma_i \Sigma_j \beta_{ij} p_i^{1/2} p_j^{1/2} + \Sigma_i \Sigma_s \beta_{is} p_i S^{1/2} + \Sigma_i p_i * (\Sigma_s \Sigma_{s'} \beta_{ss} S^{1/2} S'^{1/2})\}$$
$$+ 2 * Q^{1/2} * \{\Sigma_i \beta_{iK} p_i K^{1/2} + \Sigma_i p_i * \beta_{Kt} K^{1/2} t^{1/2} + \beta_{QK} Q^{1/2} K^{1/2} + \beta_{K\Delta K} K^{1/2} \Delta K^{1/2}\}$$
$$+ \beta_{KK} K^{1/2} K^{1/2} * \Sigma_i p_i \tag{29}$$

where $i = L1, L2, E, M$ and $S = Q, t, \Delta K$ and $t$ is time, which is assumed to be a proxy for disembodied technical change.

Shephard's Lemma allows us to derive the cost minimizing bundle of variable factors:

$$V_i = \frac{\partial G}{\partial P_i} \tag{30}$$

where $V_i$ represents the cost minimizing bundle of the $i$th variable factor ($L1$, $E$, $M$). The price of capital can be estimated from the first-order Euler equation in a dynamic context:[24]

$$P_K = -\frac{\partial G}{\partial K} - r\frac{\partial G}{\partial \Delta K} + \left[\frac{\partial^2 G}{\partial \Delta K^2}\right] * \left[\frac{\partial^2 \Delta K}{\Delta t^2}\right] + \left[\frac{\partial^2 G}{\partial K \partial \Delta K}\right] * \Delta K \tag{31}$$

where $r$ is a long run discount rate.

To construct measures of productivity growth, we begin by assessing the variable cost elasticity with respect to time ($e_{Gt}$). The negative value of this variable is equal to the rate of diminution of variable cost:

$$e_{Gt} = -\frac{\partial lnG}{\partial t} = -\frac{\partial G/\partial t}{G} = -\frac{\dot{G}}{G} \tag{32}$$

The conventional measure of technological change is expressed as the rate of diminution of the total cost function with respect to time. Total cost can be expressed as:

$$TC = VC + P_K K = G(P_E, P_M, K, \Delta K, Q, t) + P_K K \tag{33}$$

Thus, our measure of total factor productivity (TFP) growth is:

$$e_{Ct} = TFP_t = -\frac{\partial lnTC}{\partial t} = -\frac{\partial TC/\partial t}{TC} = -\frac{1}{TC}\cdot\left(\frac{G}{G}\frac{\partial G}{\partial t} + \left(\frac{\partial G}{\partial K} + P_K\right)\frac{\partial K}{\partial t}\right)$$

$$= -\frac{G}{TC}\cdot\frac{\partial G/\partial t}{G} - \frac{1}{TC}\cdot\frac{\partial K}{\partial t}\cdot\left(\frac{\partial G}{\partial K} + P_K\right)$$

$$= \frac{G}{TC}\cdot e_{Gt} - \frac{1}{TC}\cdot\frac{\partial K}{\partial t}\cdot\left(\frac{\partial G}{\partial K} + P_K\right)^{25} \quad (34)$$

In the next section of the paper, we outline a model that allow us to test whether measurement error is a significant determinant of changes in TFP growth.

## 4. Measurement Error Model

The Jorgenson-Griliches dual version of the Solow residual, described in equation (18), allows us to express the difference between observed and actual TFP growth as a function of the measurement errors of output and input prices ($P_q$ and $P_i$, $i = K, L, M, S$, respectively:[26]

$$\dot{TFP}_t - \dot{TFP}_t^* = (s_{kt})(\dot{P}_{kt} - \dot{P}_{kt}^*) + (s_{mt})(\dot{P}_{mt} - \dot{P}_{mt}^*)$$
$$+ (s_{1t})(\dot{P}_{1t} - \dot{P}_{1t}^*) + (s_{st})(\dot{P}_{st} - \dot{P}_{st}^*) - (\dot{P}_{qt} - \dot{P}_{qt}^*) \quad (35)$$

In previous sections of the paper, I have outlined hypothesized sources of measurement error of output and input prices. Using equations (2), (4), (6), (8), and (10), I can express the differences between the true and measured rates of growth of the prices of output, capital, materials, services, and labor as:

$$\dot{P}_{qt} - \dot{P}_{qt}^* = \epsilon_{pq} = \beta_Q \text{NEWPROD}_i \quad (36)$$

$$\dot{P}_{kt} - \dot{P}_{kt}^* = \epsilon_{pk} = \beta_K \text{COMPINV}_i \quad (37)$$

$$\dot{P}_{mt} - \dot{P}_{mt}^* = \epsilon_{pm} = \beta_{M1} \text{SUPPCOMP}_i + \beta_{M2} \text{FORMAT}_i \quad (38)$$

$$\dot{P}_{st} - \dot{P}_{st}^* = \epsilon_{ps} = \beta_{s1} \text{SELSERV}_i + \beta_{s2} \text{RATCAO}_i \quad (39)$$

$$\dot{P}_{1t} - \dot{P}_{1t}^* = \epsilon_{p1} = \beta_L \text{QUALIND}_i \quad (40)$$

Substituting equations (36)–(40) into (35) and rearranging terms yields the following expression:

$$\dot{TFP}_t = \dot{TFP}_t^* + \beta_K s_{kt} \text{COMPINV}_i + \beta_L s_{1t} \text{QUALIND}_i + \beta_{M1} s_{mt} \text{SUPPCOMP}_i$$
$$+ \beta_{M2} s_{mt} \text{FORMAT}_i + \beta_{S1} s_{st} \text{SELSERV}_i + \beta_{S2} s_{st} \text{RATCAO}_i - \text{B}_Q \text{NEWPROD}_i \quad (41)$$

Given that the central issue of this paper is whether the measurement problem has become more serious over time, we derive the following expression for the difference between measured and actual acceleration in TFP between year $t$ and $t + 1$:

$$(\dot{TFP}_{t+1} - \dot{TFP}_t) = (\dot{TFP}_{t+1} - \dot{TFP}_t^*) - \beta_q(\text{NEWPROD}_{i,t+1} - \text{NEWPROD}_{it})$$

$$+ \beta_k(s_{k,t+1}\text{COMPINV}_{i,t+1} - s_{kt}\text{COMPINV}_{it}) + \beta_l(s_{l,t+1}\text{QUALIND}_{i,t+1} - s_{lt}\text{QUALIND}_{it})$$

$$+ \beta_{m1}(s_{m,t+1}\text{SUPPCOMP}_{i,t+1} - s_{mt}\text{SUPPCOMP}_{it}) + \beta_{m2}(s_{m,t+1}\text{FORMAT}_{i,t+1} - s_{mt}\text{FORMAT}_{it})$$

$$+ \beta_{s1}(s_{s,t+1}\text{SELSERV}_{i,t+1} - s_{st}\text{SELSERV}_{it}) + \beta_{s2}(s_{s,t+1}\text{RATCAO}_{i,t+1} - s_{st}\text{RATCAO}_{it}) \quad (42)$$

Although the actual acceleration of TFP is unobservable, we do observe the industry's rate of investment in process R&D, which has been viewed in the R&D literature as a proxy for this variable.[27] Empirical studies [see Griliches-Lichtenberg (1984a)] report a strong positive correlation between process innovation and acceleration of productivity growth. Thus, we proceed with estimation of equation (42) under the assumption that process innovation is the best available indicator of acceleration in TFP.

## 5. Empirical Results

Descriptive statistics for estimates of the acceleration in TFP during the 1980s, for 450 manufacturing industries, are presented in Table 4. Note that 7 different measures have been computed, based on the procedures outlined in Section 3. Recall that the Solow residual and the index number estimates are calculated from the reported factor shares,[28] while the remaining measures are derived from econometric estimation. The econometric results should be interpreted with caution since the parameter estimates would be inconsistent if there are errors in the price terms. Hence, the econometric estimates of productivity growth may be measured imprecisely. The values reported in the first row are the Solow residual calculations. Rows two through five contain the index measures of TFP based on the production or cost function, using either the translog or generalized Leontief functional form. Row six reports results from econometric estimation of a generalized Leontief production function.

The last row consists of the full dynamic estimates that incorporate the effects of adjustment costs of capital, which is treated as a quasi-fixed input. Rather than us a residual measure of capital and the corresponding ex-post measure, we have estimated an ex-ante measure of capital, following procedures outlined in Berndt and Wood (1984). Six equations from (30), (31), and (32) were estimated using iterative three stage least squares.

To estimate this model, we used lagged values of the arguments of the cost and demand functions as instruments. We allow for heterogeneity across industries in the cost function parameters by estimating separate regressions for each two-digit sector. The model fits well and the cost function parameters have the expected signs and magnitudes that are similar to those presented in recent studies by Morrison (1988b, 1990), using more highly aggregated data.[29]

*Table 4.* Descriptive statistics and correlation matrix for estimates of acceleration in TFP during the 1980s (difference between 79–89 growth rate and 73–79 growth rate) based on alternative estimation procedures for 450 manufacturing industries.

Descriptive Statistics

| | Descriptive Statistics (in %) | | | | |
|---|---|---|---|---|---|
| Method of TFP Estimation #* | Mean | Median | Std Dev | Minimum | Maximum |
| (1) Solow residual | 0.66 | 0.50 | 2.91 | −7.59 | 13.64 |
| (2) Index measure based on translog production function | 0.55 | 0.41 | 2.91 | −7.79 | 16.36 |
| (3) Index measure based on generalized Leontief production function | 0.55 | 0.41 | 2.90 | −7.80 | 15.11 |
| (4) Index measure based on translog cost function | 0.89 | 0.56 | 2.78 | −5.20 | 22.06 |
| (5) Index measure based on generalized Leontief cost function | 0.92 | 0.63 | 2.79 | −5.20 | 21.64 |
| (6) Econometric estimation based on generalized Leontief production function | 0.55 | 0.43 | 2.84 | −4.89 | 14.75 |
| (7) Econometric estimation based on generalized Leontief dynamic cost function | 0.70 | 0.66 | 2.82 | −2.95 | 15.48 |

Correlation Matrix

| Correlations | | | | | | |
|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| 1.00 | | | | | | |
| .97 | 1.00 | | | | | |
| .98 | .94 | 1.00 | | | | |
| .71 | .65 | .66 | 1.00 | | | |
| .71 | .66 | .66 | .90 | 1.00 | | |
| .67 | .64 | .60 | .54 | .63 | 1.00 | |
| .66 | .65 | .59 | .53 | .62 | .72 | 1.00 |

The descriptive statistics imply that our detailed industry estimates of growth and acceleration in TFP are consistent with the aggregate figures cited in the introduction to the paper. That is, the results also indicate an improvement in manufacturing productivity in the 1980s. Using a series of different estimation procedures described in the previous section, we find that the representative industry experienced an average annual acceleration in TFP of approximately 3/4 of a percentage point during the 1980s.

The bottom of Table 4 contains a series of correlation coefficients for the productivity measures. Since the statistical distributions of a number of the measures are quite similar, we can reduce the measures of acceleration that we use to estimate the measurement error model. Specifically, we will focus on results based on the Solow residual and generalized Leontief index and cost function measures.

OLS and GLS estimates of the measurement error model described in equation (42) are presented in Tables 5 and 6, respectively. The GLS estimation uses the standard error of the estimate as weights, since the disturbance terms could be heteroskedastic. Recall that the dependent variable is acceleration in TFP (for 364 manufacturing industries).[30] If systematic underestimation of input growth has occurred during the 1980s, we expect to find that the change in productivity growth is positively correlated with a set of variables that are proxies for this understatement. The empirical evidence does not appear to be consistent with this hypothesis.

Estimation of this model indicates that measurement error does not explain a substantial percentage of the acceleration in productivity. For both the OLS and GLS results, the coefficients on the measurement error proxies are all insignificant, some do not have the expected signs, and the $R^2$ values are quite low. Process Innovation is the only variable with a statistically significant coefficient, but this is not a measurement error indicator. Our findings are also invariant to the method of TFP measurement. Roughly the same pattern of results emerged when we estimated the same model, allowing for different intercepts across two digit sectors.

The results do not necessarily imply that measurement errors are unimportant, only that they may cancel out in a measure of TFP growth. For example, innovative industries may generate new products, which raises product quality, leading to understatement of real output growth, since many of these quality changes are not reflected in the output deflators. However, the quality of capital, labor, and other inputs is also likely to be improving in these sectors, implying that real input growth will also be understated. Thus, the net effect on measured TFP growth could be quite small.

## 6. Conclusions

Recent trends such as outsourcing, an increase in the rate of investment in computers, and unmeasured changes in the quality of output and the labor force may have exacerbated errors in the measurement of total factor productivity (TFP). Detailed industry data are examined to test whether the acceleration in manufacturing productivity growth is related to a set of proxy variables for output and input price mismeasurement. The findings are inconsistent with this hypothesis. That is, it appears that the improvement in manufacturing productivity cannot be explained by measurement error. This result is consistent with previous work by Baily and Gordon (1988), who concluded that measurement errors, though relatively serious, are fairly constant over time. Thus, it is unlikely that major trends in the productivity data can be attributed to this phenomenon.

An important caveat must be noted: these findings could be highly sensitive to the choice of proxies for mismeasurement. If our theories concerning how these measurement errors arise are invalid, or the data are imprecise, then our results could be spurious.

One interesting extension of this analysis would be to examine differences in the parameters of the measurement error models across industries. Our estimates are based on the

*Table 5.* OLS estimates of measurement error model (equation (42) in text).

OLS Estimation
Dependent Variable: Acceleration in TFP during the 1980s

| | Method of Total Factor Productivity Estimation | | | |
|---|---|---|---|---|
| | Index Measures | | | Econometric Measure |
| | | Production Function | Cost Function | Cost Function# |
| Coefficient on Measurement Error Proxy | Solow Residual | Generalized Leontief | Generalized Leontief | Generalized Leontief |
| Output | −.0026 | −.0023 | −.0041 | .0070 |
| | (.0051) | (.0058) | (.0046) | (.0082) |
| Capital | −.0734 | .0129 | −.0092 | .0101 |
| | (.3561) | (.4689) | (.3388) | (.5287) |
| Labor | −.0024 | −.0010 | .0004 | .0009 |
| | (.0020) | (.0023) | (.0021) | (.0025) |
| Foreign Materials | −.0426 | .2954 | −.3566 | .3522 |
| | (.2199) | (.4356) | (.4321) | (.4467) |
| "High Tech" Materials | −.0162 | −.0195 | −.0120 | .0062 |
| | (.0140) | (.0167) | (.0112) | (.0132) |
| Purchased Services | .0377 | .0468 | .0238 | .0156 |
| | (.0486) | (.0521) | (.0521) | (.0681) |
| Central Office Employment | .0220 | .0245 | .0221 | −.0184 |
| | (.0243) | (.0341) | (.0243) | (.0227) |
| Process Innovation | .3270* | .3562* | .3765* | .3611* |
| | (.0831) | (.0934) | (.1021) | (.0975) |
| Intercept | .0038 | .0042 | −.0007 | .0123* |
| | (.0029) | (.0034) | (.0022) | (.0056) |
| $R^2$ | .0529 | .0532 | .0552 | .0624 |

#Dynamic cost function (capital fixed and adjustments costs).
*Significant at the .01 level.

| Measurement Error Proxy | Definition | Time Period |
|---|---|---|
| Output | New products as a % of existing products | 1982–1987 |
| Capital | % of new capital expenditures devoted to computers | 1982–1987 |
| Labor | Acceleration in quality index | 1979–1989 |
| "High Tech" Materials | Weighted average of computer investments undertaken by industry's suppliers | 1982–1987 |
| Foreign Materials | % of foreign mateirals consumed in production | 1982–1987 |
| Purchased Services | Change in the ratio of selected purchased services/industry output | 1982–1987 |
| Central Office Employment | Change in the ratio of central office employment/total employment | 1982–1987 |

| Proxy for Acceleration in TFP | Definition | Time Period |
|---|---|---|
| Process Innovation | Process R&D intensity | 1974 |

*Table 6.* GLS estimates of measurement error model (equation (42) in text).

GLS Estimation
Dependent Variable: Acceleration in TFP during the 1980s

| | Method of Total Factor Productivity Estimation | | | |
|---|---|---|---|---|
| | Index Measures | | | Econometric Measure |
| | | Production Function | Cost Function | Cost Function# |
| Coefficient on Measurement Error Proxy | Solow Residual | Generalized Leontief | Generalized Leontief | Generalized Leontief |
| Output | −.0034 | −.0047 | −.0022 | .0035 |
| | (.0059) | (.0062) | (.0053) | (.0062) |
| Capital | −.0182 | .0110 | .0538 | −.0577 |
| | (.3997) | (.3565) | (.4389) | (.5342) |
| Labor | −.0035 | .0008 | −.0014 | −.0064 |
| | (.0045) | (.0021) | (.0011) | (.0038) |
| Foreign Materials | −.0832 | −.4211 | .2201 | −.0576 |
| | (.5021) | (.3722) | (.3356) | (.4232) |
| "High Tech" Materials | −.0203 | −.0105 | −.0245 | −.0068 |
| | (.0167) | (.0111) | (.0167) | (.0208) |
| Purchased Services | .0450 | .0321 | .0621 | −.0121 |
| | (.0356) | (.0420) | (.0569) | (.0367) |
| Central Office Employment | .0162 | .0198 | .0203 | −.0321 |
| | (.0222) | (.0179) | (.0254) | (.0198) |
| Process Innovation | .4020* | .4100* | .3897* | −.4001* |
| | (.1011) | (.1133) | (.0987) | (.1021) |
| Intercept | .0036 | .0011 | .0034 | .0055* |
| | (.0028) | (.0017) | (.0022) | (.0026) |
| $R^2$ | .0610 | .0622 | .0643 | .0651 |

#Dynamic cost function (capital fixed and adjustments costs).
*Significant at the .01 level.

| Measurement Error Proxy | Definition | Time Period |
|---|---|---|
| Output | New products as a % of existing products | 1982–1987 |
| Capital | % of new capital expenditures devoted to computers | 1982–1987 |
| Labor | Acceleration in quality index | 1979–1989 |
| "High Tech" Materials | Weighted average of computer investments undertaken by industry's suppliers | 1982–1987 |
| Foreign Materials | % of foreign mateirals consumed in production | 1982–1987 |
| Purchased Services | Change in the ratio of selected purchased services/industry output | 1982–1987 |
| Central Office Employment | Change in the ratio of central office employment/total employment | 1982–1987 |

| Proxy for Acceleration in TFP | Definition | Time Period |
|---|---|---|
| Process Innovation | Process R&D intensity | 1974 |

assumption that the regression parameters are the same for each industry. The detailed industry data provide enough degrees of freedom to estimate these models separately by two-digit SIC industry. This will enable us to determine whether the biases (if they exist) are concentrated in specific sectors. Still, the aggregate impact of these measurement errors does not appear to be substantial.

## Data Appendix

### A.1. Productivity Data

The primary source of data for this study is the National Bureau of Economic Research's (NBER) Productivity File, which includes current and constant-dollar measures of output and inputs for 450 manufacturing industries for the years 1958–1989. Five inputs can be measured: capital, production labor, nonproduction labor, materials (or intermediate goods purchased from other firms), and energy. Conventional cost or production functions can be estimated based on these data.[31] This file is an updated version of the Penn-SRI Database created at the Census Bureau in the late 1970s. An earlier version of this file has been analyzed in Siegel-Griliches (1992) and Siegel (1994).

Data on interindustry transaction are derived from the 1982 and 1987 Products and Materials Files from the Census of Manufactures. These files contain detailed data on the consumption of materials in the production process for 450 4-digit SIC manufacturing industries.[32] For these same industries, data on investment in computers was obtained from the Census of Manufactures in 1977, 1982, and 1987. These data will be used to construct estimates of the rate of investment in computers by the home industry and investments undertaken by an industry's suppliers of materials inputs.

### A.2. Measurement Error Proxies

*New Goods*

For the section of the study that deals with output price mismeasurement, I have estimated the number of new goods created within 4-digit sectors, based on an examination of lists of products from quinquennial Censuses of Manufactures in 1972, 1977, and 1982.[33] In the empirical analysis, we will assume that errors of measurement of the output price are more severe in sectors that are generating a substantial proportion of new goods.

Two alternative definitions of new products were used. One definition requires that a product appear for the first time in the Census publications or had its specification changed. The term *specification*, apart from denoting technical properties, also includes packaging, color, weight, and similar characteristics. The second definition also considers the economic significance of the market for a specific product. That is, a product can be defined as new as the result of a split of a product class (5-digit SIC) into a number of products, which may have existed during the previous Census (1977), but were not listed separately. Therefore, the second definition includes the products defined earlier and also products that existed during the previous period, but were not considered important enough (usually because output was relatively low) to warrant a separate listing. Similarly, we consider the antithesis of this phenomenon, or the contraction of a number of products into only one product class. The notion of an increasing demand for a product is taken to represent a quality change in the sense that an industry is providing the consumer with a new or improved product.

*Labor Quality Indexes*

In constructing these indexes, the key data requirements are a set of employment attributes to identify different types of labor. Ideally, we would like to observe a large set of such characteristics (sex, age, education, occupation, . . .) for workers in 4-digit SIC industries. Unfortunately, we found that there is a severe tradeoff between industry detail and labor composition detail.[34] After some frustrating attempts to construct indexes at the 3- or 4-digit SIC level, we decided to work with demographic data on the characteristics of workers in 21 (mainly 2-digit SIC) manufacturing industries that was provided to us by Larry Rosenblum of the BLS's Productivity Division.[35] These data cross-classify labor input by two age and four education categories, separately, for production and nonproduction workers.[36] The two age cells are:

a) 15–40 years of age and
b) 41+ years of age

The four education cells are:

a) without a high school diploma
b) with exactly a high school diploma
c) with some college
d) with a college degree

*"High-Tech" Materials*

To derive a measure of SUPPCOMP, I use data from the Census of Manufactures on detailed usage of materials [see Siegel-Griliches (1992) for further details]. The following example illustrates the methodology: Assume that industry A purchases two materials inputs from industries B and C, respectively. The inputs purchased constitute 40% and 50% of industries B and C's output, respectively. Assume also that industries A and B each devoted 60% of their capital expenditures to computers. Given these figures, our measure of computer investments embodied in the mateirals input of industry A would be $(.40 * .60) + (.50 * .60) = .54$.

Note that these calculations impose several strong assumptions on the nature of the technology transfer that occurs between an industry and its customers. For example, it is assumed that the distribution of interindustry "benefits" of investment in computers is homogeneous and proportional to the share of industry output represented by a given transaction.

Homogeneity is a fairly strong assumption, given that some products are inherently "low-tech," while others may require substantial computer input. Therefore, industry *j*'s investment in computers could yield benefits to industry *i* that differ substantially from those accruing to other industries. In future, I hope to construct a spillover measure that adjusts for these differences.

*R&D Investment*

Scherer (1984) has constructed a file containing data on process innovation at the 3-digit SIC level for the year 1974. The Scherer data distinguish between R&D by industry of origin and R&D by industry of use. Our measure of process innovation is the industry's own process R&D.

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**Notes**

1. The average annual growth rate of manufacturing productivity in the pre-slowdown period (1948–1973) was 2.2% and 0.7% during the slowdown (1973–1979)—Source: Bureau of Labor Statistics Productivity Measures for Selected Industries, 1958–1988.
2. Since our empirical analysis is based on 4-digit SIC level data, we calculated weighted (by value added) TFP measures over the same time periods [following Domar (1960)]. Our estimates of aggregate manufacturing TFP growth are smaller in magnitude but the trends are similar: 0.0% during the slowdown period, 0.8% over the 1980s, and 1.1% between 1985 and 1989. These findings are not driven by high rates of productivity growth in the computer industry (SIC 3573), since the results are virtually identical when we exclude this sector.
3. Conventional estimates of TFP do not include purchased services as an input. However, recent empirical studies, including Gullickson and Harper (1987), and Morrison and Berndt (1991) have included purchased services as an input in cost or production function estimation. These studies used the BLS 2-digit SIC KLEMS dataset, which includes price and quantity measures for purchased services.
4. Two recent studies provide some empirical evidence on this issue. Lichtenberg and Griliches (1989) and Siegel (1994) conclude that the Producer Price Index (PPI) adjusted for approximately 60% of the change in product quality that occurred over a ten-year period. Siegel (1994) finds that the magnitude of the mismeasurement of quality change has not varied over time.

5. Time subscripts have been suppressed for simplicity.
6. Lichtenberg and Griliches (1989) and Siegel (1994) use new products as indicators of change in product quality. As discussed in Ruggles (1977), the error in output price could also be related to sampling error in the PPI. Unfortunately, these data are unavailable.
7. Typically, we would expect that these are downward movements. Diewert (1987) provides some examples of how new goods bias can distort inflation statistics.
8. See Trajtenberg (1990) for a discussion of these issues and empirical evidence on price mismeasurement for CAT scanners.
9. I focus on the median values because (as shown on the table) there were some new industries created during the sample period.
10. For simplicity, time subscripts are suppressed for the remainder of the paper.
11. Recall that these values could actually understate the "true" rate of investment in computers because they do not include complete adjustments for quality changes in computers.
12. Capital intensity (ratio of capital to output) relates specifically to equipment: we exclude (physical) plant or structures from the calculations.
13. Another way to state this hypothesis is that errors in output deflators are "transmitted" to materials deflators. Following a suggestion by a referee, we have constructed a proxy for the materials price error that is based on the output price error of the supplying industries. The results did not change appreciably.
14. Details on the construction of SUPPCOMP and FORMAT are contained in the data appendix.
15. These findings were disputed in Griliches and Lichtenberg (1984), who used a measurement error framework to test for interindustry spillovers. The authors conclude that the evidence for R&D spillovers is, at best, weak.
16. For example, Bartelsman, Caballero, and Lyons (1991) find that the activity of an industry's suppliers has a significant impact on its productivity growth.
17. 350 out of 450 industries reported higher values in 1987 that in 1982.
18. See Lichtenberg and Siegel (1990) for a description of the role of central office establishments. Data on central offices are also presented in Siegel-Griliches (1992).
19. As discussed in Siegel-Griliches (1992), selected purchased services are those that are most closely associated with enhancement of the productivity of the establishment's capital stock. These include three types of services that can be outsourced by companies—repair and maintenance of plant, repair of equipment, and communication services. The data are desirable because they constitute the only information on purchased services that is directly reported by manufacturing establishments.
20. The central office data are reported at the 2-digit SIC level, so we assume that this ratio is the same for all 4-digit industries within the same 2-digit sector.
21. For example, an increase in the proportion of hours worked by more highly educated workers is hypothesized to reflect an increase in labor quality.
22. These indices are calculated at the industry level. We have suppressed industry subscripts to avoid confusion.
23. Details on the construction of the indexes are contained in the data appendix.
24. See Morrison (1988), equation (13), p. 281.
25. Note that when a temporary equilibrium coincides with a long-run equilibrium, $(\partial G/\partial K + P_K) = 0$. Under these conditions, equation (35) reduces to:

$$e_{Ct} = \frac{G}{TC} \cdot e_{Gt}$$

26. We have suppressed industry subscripts.
27. Note that if the true acceleration of TFP is uncorrelated with the measurement error indicators, then parameter estimates of equation (42) are unbiased, even with an omitted variable. Correlation coefficients for the complete set of measurement error proxies [as defined in equation (42)] and industry measures of process R&D provided in Scherer (1984) reveal that the measurement error indicators are not strongly correlated with process R&D.
28. Capital's share is calculated as a residual.
29. The methodology differs slightly from Morrison (1988b), since we do not estimate input share equations.
30. Only 364 out of 450 industries reported consistent data.
31. See Gray (1989) for full documentation of these data.

32. We may also construct an alternative matrix of interindustry transactions from the Bureau of Economic Analysis's (BEA) 1977 and 1982 detailed "Make" and "Use" input-output tables. A concordance file can be used to map these transactions into the 450 manufacturing industries and 10 2-digit SIC nonmanufacturing sectors. See Bartlesman, Caballero, and Lyons (1991) for further details.
33. These measures were derived by analyzing the Census Bureau publications: "Numerical List of Manufactured and Mineral Products'' for 1972, 1977, and 1982." Appendix B of the 1982 report, entitled "Comparability of Product Codes," was used to establish matches and nonmatches across Censuses. I am indebted to Zoe Georganta for performing this analysis and providing me with these data.
34. Most of the data on the characteristics of industrial workers is derived by the Current Population Survey (CPS). In some years, there are fewer than 50,000 observations with wage data. If we try to cross-classify labor input along many dimensions, we will not have enough degrees of freedom to present reliable estimates. In fact, if we had adopted this approach, we would have many cells without any observations.
35. These data have been analyzed in Berndt, Morrison, and Rosenblum (1992).
36. Thus, in the context of our notation, there are 16 types of labor input or $i = 16$ $(2 * 2 * 8)$.

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