ENDOGENOUS TECHNOLOGICAL ADVANCE AND POSTWAR ECONOMIC GROWTH: A PRODUCTION FUNCTION ANALYSIS

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I. INTRODUCTION

A central issue in the determination of long-term growth rates is the role of technological advance. It is well established that on the supply side, about one-third of postwar growth in the United States is an unexplained residual — multifactor productivity in the national income accounts — which is understood to encompass technological advance, although the two measures are not coterminous. In many studies, the rate of technological advance has been approximated as a deterministic trend, either fitted to the residual or multiplying one of the other factor inputs. Deterministic models, however, are unsatisfactory for two reasons. First, on theoretical grounds, technological advance should be considered endogenous [Kramer, 1988]. Second, on empirical grounds, the existing measures of technological advance all exhibit stochastic behavior. This paper specifies a growth model in which the rate of technological advance is determined by the flow of services from the Research and Development (R&D) stock. In this framework, it is established that technology can account for a substantial share of the residual variation in output. The residual can be further reduced by taking the public sector capital stock into account. Section II examines the issues of technological advance in the production function. Section III specifies the model for the R&D stock. Section IV discusses the estimation procedure. Section V estimates the contributions of R&D and government capital to growth.

II. THE PRODUCTION FUNCTION

A useful starting point for analyzing the impact of technological advance on economic growth is the neo-classical framework originated in Solow [1957]. The production function is in two factors ($K, L$), but can be generalized to any arbitrary order. Let $X$ denote the factor inputs of a $j$-order production function, and let $t$ denote a deterministic time index:

$$\partial \ln Y / \partial t = \gamma_t = \left[ \partial Y / \partial t \right] Y - \Sigma \left[ P \cdot X \right] Y / \left[ \partial X / \partial t \right] Y$$

where $Y$ = real output and $P$ = price. The corresponding log-linear production function is simply:

$$\ln Y = a + \Sigma \alpha_p \ln X_p + \mu_t$$

where $a_p$ = elasticities of output with respect to inputs.


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Note that \( \Delta X / \Delta Y \) equates to \( \Delta X / \Delta Y \). It is convenient to simplify this expression by defining an input function \( (\Delta Y) \) and to the size of the factors, \( \Delta Y \) = \( \sum_{i=1}^{N} \Delta Y_i \). The sum of the \( \Delta Y_i \) coefficients determines the degree of homogeneity of the input function with constant returns to scale (CRS), \( \Delta Y_i = 1 \). The production function residual can also be obtained from the associated cost equation:

\[
\frac{\Delta C_i}{\Delta Y_i} = \frac{\Delta C_i}{\Delta Y_i} = \frac{\Delta C_i}{\Delta Y_i} \cdot \frac{\Delta Y_i}{\Delta Y_i} = \frac{\Delta C_i}{\Delta Y_i} \cdot \frac{\Delta Y_i}{\Delta Y_i}
\]

where \( C_i \) is costs. The production function residual captures changes in output that are not attributable to factor inputs. The cost function residual measures changes in costs that are not accounted for by changes in input prices. Under highly specific conditions, the residuals from the cost and output equations equate (\( \Delta Y_i = \Delta C_i \)). This equality, however, requires profit maximizing behavior, competitive markets, and CRS. If any of those conditions are violated, for instance if returns to scale are nonconstant or if firms minimize costs rather than maximize profits, this equality does not hold.

It is immediately apparent that the residuals can be influenced by factors other than technological advance. When applied to the postwar period, the residual term can vary as a result of changes in the cost or volume of intermediate materials netted out in the computation of value-added. In this respect, the experience of the 1970s demonstrated that shocks to the prices of intermediates such as energy may induce cyclical losses in activity and factor substitutions that show up as variations in the residual. Other possible factors include the public sector capital stock.

Reduced to the essentials, the investigative problem is to dissect the rate of technological advance from other factors influencing residual variation. In the original Solow (1957) formulation, technological advance was modeled as a deterministic trend with the remaining component attributable to random perturbations. Because CRS and perfect competition imply diminishing marginal returns to investment, this model had the property that in the long run, growth rates are determined by population and technology with output ultimately evolving toward the exogenous trend. The assumption of disembodied or Hicks-neutral technological advance is of course not inherent in the model; technological advance can be embodied and augmenting with respect to a particular factor. However, the implications for long-term growth are comparable. Solow (1957) demonstrates that in the long run the properties of CRS models with embodied and disembodied technology are identical, although the short-term dynamics may differ. Instead, the inherent limitation in this paradigm lies with the assumption that technology is deterministic.

Dissection with deterministic exogenous technology has led to renewed interest in a competing explanation for the residual, returns to scale. Several arguments have been proposed to explain why returns may be increasing. Romer (1986) and Rebelo (1990) suggest externalities from investment. Lucas (1988) proposes an externality from human capital, while Barro (1990) suggests spillovers from government investment or subsidies to industry. Indirect evidence of spillovers from capital is presented in DeLong and Summers (1991). In this study, the postwar growth rates of a large sample of countries are found to be highly correlated with equipment investment, and growth rates in the more advanced countries are identified as higher than would be consistent with CRS. Scale effects are also implied by studies comparing trade regimes (Houba and Sala-i-Martin, 1991). Higher growth rates in countries practicing outward-oriented developmental strategies may reflect scale advantages from market deepening. Yet another scale-related argument has to do with administered pricing, inasmuch as firms can avoid diminishing marginal returns to investment with monopolistic than perfect competition. Originally proposed in Hall (1990), the divergence between marginal costs and actual pricing has been exploited in Morrison (1989a,b, 1990) to estimate the contribution of scale factors directly. Even this approach, however, does not directly isolate the technological component in the residual, which is still found to exhibit high degrees of cyclical variation with periodic negative growth.

The problems in attempting to isolate technological advance on the basis of the production function residual suggest that it may be preferable to estimate technological advance directly using existing empirical measures. The existing measures of disembodied technological advance include R&D spending, patents — analyzed extensively in Grilliches (1990), and indexes of scientific knowledge based on published research (Acheson, 1980). Of these, R&D is more analytically tractable in a production function since it is an expenditure flow, and a rental price can be calculated. Nevertheless, the specification problems involved here are substantial. As noted in Grilliches (1979), potential issues include (1) determining the appropriate measure of R&D, specifically whether R&D should be limited to spending by private industry or include that of other institutions; (2) determining the cost of R&D, which involves choice of a deflator and construction of a rental price; (3) determining the degree of technical change as opposed to merely physical depreciation of the R&D stock; and (4) specifying the lag length between R&D and its impact on real economic activity. Each of these issues is addressed below.

Simultaneously, the idea that the public-sector capital stock would generate spillovers has recently led to attempts to measure its impact directly. The elasticity of output with respect to government capital has been estimated as in the range of 0.3 to 0.4 using time-series methods (Aschauer, 1989). Other studies have identified smaller effects, but have provided evidence of significant reductions in capital costs (Nadiri and Mannes, 1991). Estimates based on time-series methods, however, shirk signs of upward bias, either due to variable omission or collinearity. For this reason, estimation is by factor shares (see below). Since the most important component of the non-military government capital stock is infrastructure, the mnemonic \( \text{I}_1 \) will be used.

The model to be estimated, therefore, is as follows. The production function is in four factors \( (X, L, R, F) \). In this model, initial reservations are imposed on the input elasticities, allowing returns to deviate from unity. No priors are imposed as to whether technology is disembodied or factor augmenting; this will be ascertained from the estimates. This yields, in log-linear form:

\[
\ln Y_t = a_0 + a_1 \ln L_t + a_2 \ln K_t + a_3 \ln R_t + a_4 \ln F_t + u_t
\]

III. THE DETERMINATION OF R&D INVESTMENT

Data Definitions

The R&D data is compiled in National Science Foundation, NSF (1990); R&D is defined as research in the physical and biological sciences, including the medical and engineering fields. The NSF survey limits funds reported under R&D to current operating costs, covering salaries and non-wage compensation, supplies and overhead. It specifically excludes capital expenditures by industry and other private institutions. R&D is calculated net of physical depreciation. The data is available on an annual basis.
beginning in 1953 and are estimated through 1990. While the current dollar data is converted to constant dollars using the GNP deflator in NSF [1992], the cost of research has risen somewhat more rapidly on average than the inflation rate for the economy as a whole, with the result that this overstates the real volume of R&D. Two deflators for industrial R&D using the Paasche and Laspeyres weighting techniques are available in Jankowski [1992] from 1969 onward. The index used here is a Fisher ideal index, i.e., the geometric mean of the Paasche and Laspeyres deflators. In order to obtain price indexes for the entire period in this study, they are backcast to 1953 using their own leads and the GNP deflator as a regressor. Both deflators are normalized on 1982. In the NSF [1992] data, three main sources of funds can be identified: (1) private industry, (2) non-profit institutions, including universities, and (3) the federal government, including federally-funded nonprofits. For reference, these will be denoted \( R_s \), \( R_p \) and \( R_g \) respectively. Further, a substantial share of R&D funded by the government is performed by industry (hereafter, \( R_p \)); this distinction becomes important in the computation of the stock.\(^{\text{a}}\)

**The User Cost of R&D**

The user cost of R&D is based on the well-known expression for the cost of capital derived in Hall and Jorgenson [1967], which aggregates prices, tax mechanisms, and the cost of funds. Let \( P \) be the price of R&D, \( T \) the marginal tax rate on industry, \( ITC \) the investment tax credit, if applicable, \( DA \) present value of depreciation allowances, \( IF \) expected inflation, \( CP \) cost of funds, \( ED \) the rate of economic depreciation, where all tax rates are expressed as decimals. The basic expression for the cost of capital is:

\[
C_p = P \times (1 - ITC) \times (DA \times V_F (CP, IF) + ED \times (1 - T))
\]

\[(5a)\]

The cost terms corresponding to the four R&D measures are dissimilar. For \( R_s \), the appropriate measure is a user-cost aggregating prices, tax mechanisms and the cost of funds to the firm (hereafter \( C_s \)). Under current tax law, R&D is expensed rather than capitalized and depreciated. The R&D data used in the regressions is measured net of physical depreciation. Consequently, assuming that physical depreciation exhausts technical depreciation, \( DA + ED \) drops out. An ITC was available for R&D in 1981-91, at rates varying between 20 percent and 25 percent, on the increment in R&D spending over a three-year average. Because of the incremental structure of the credit and the moving base, the effective rate was considerably lower than the marginal rate. In the calculation of the user cost, an estimate of the effective rate was used rather than the marginal rate. For the period 1981-86, the ITC term has an average value of .035; in 1987-90, this declines to an average value of .021. In other words, the user cost estimated here incorporates the average effective impact of the ITC, rather than its impact at the margin. This yields the simpler expression:

\[
C_s = P \times (1 - ITC) \times (DA \times V_F (CP, IF)) \times (1 - T)
\]

\[(5b)\]

For research performed in industry but funded by the government, the cost of funds to the firm \( (CP, IF) \) drops out where the ITC is inapplicable, yielding:

\[
C_{gm} = P \times (1 - T) \times (1 - T)
\]

\[(5c)\]

which simplifies to \( C_{gm} = P \).

**Technological Advance**

Some specifications of the user cost have included a term for the tax gain from leverage. This was assumed here, but was found to impart excessive volatility to the resulting user-cost measure, resulting in periodic negative values. Finally, for \( R_s \) and \( R_g \), the acquisition cost of funds to the firm and the tax treatment of income are irrelevant; the cost of research is, therefore, simply its price.

In the empirical implementation of the user cost, the price of R&D is the Fisher deflator for research. \( CP \) is modeled as a function of interest rates plus a risk premium, on the assumption that the level of interest rates affects decisions at the margin whether to invest in capital assets or financial instruments. Here, \( CP \) is defined as the interest rate on corporate AAA bonds, adjusted for tax rates on capital gains and interest income, plus a risk premium. Expected inflation is defined as the fitted values of a regression of the rate of change of the implicit price deflator for nonfarm output on its own lags over two years.

**The Response of R&D to the User Cost**

From production theory, if markets are competitive the equilibrium ratio of inputs to output equals the ratio of the input elasticity to its price, i.e., \( Y_k / Y = (\alpha_k / P_k) \), where \( P_k \) is the price of the input and the prime denotes the equilibrium value. Then the increment in the input is \( \Delta X_k = \Delta(Y_k / Y) \) which equates by the chain rule to \( \Delta X_k = (Y_k \Delta Y_k / Y) \Delta Y_k \). The first term in this derivation, \( Y_k \Delta Y_k \), is the accelerator, and expresses the amount of the input required to produce a given increment in output. By inference, the elasticity of \( Y_k \) with respect to \( Y \) should be unity. The second term, \( Y_k \Delta Y_k \), is the increment in \( X_k \) associated with the convergence of \( Y_k / Y \) to its equilibrium value following a change in \( Y \). Further, using the identity given above, the ratio of the input to output \( (X_k / Y) \) varies as a function of the input cost, again with an implied elasticity of unity. In order to verify that the elasticities are consistent with their theoretically predicted values, the following regression was estimated for the two measures of the R&D stock, using the corresponding values of the user cost:

\[
\ln R_s - \ln Y = \alpha s + \alpha_s \ln C_p + \mu_s
\]

The estimated values for \( \alpha_s \), i.e., the elasticity with respect to the user cost were 1.94 and 0.983 for the larger and smaller measures of the R&D stock. These findings were robust to the serial correlation correction, which left the elasticity unchanged despite values of rho in the area of 0.86 to 0.89. In each instance, an F-test was computed for the null hypothesis that the true elasticity was unity. The null could not be rejected at standard levels of significance. This finding is significant — when coefficients in this regression are consistent with their theoretical values, the input elasticities in the production function can be estimated by factor shares, as defined below. Conversely, values significantly different from unity would render the factor shares procedure suspect.

**Compiling the R&D Stock**

Computing the stock of R&D involves imposing some identifying restrictions as to the concepts that should be represented and the rate of technical depreciation. A narrow measure of the R&D stock would include only research funded by the private
sector and nonprofit, on the grounds that federally-funded R&D has been predominantly defense related, with minimal applicability to other sectors. A broader definition would include all research actually performed by industry, on the grounds that the private sector has access to the resulting stock of knowledge. Prior studies have found widely varying rates for governmentally funded research as a determinant of private sector activity. For instance, Levy and Terleckyj (1983) maintain that federally supported research has significantly smaller effects on economic activity than privately funded R&D. Conversely, Griliches (1980, 1986) finds that total R&D explains a greater share of the variance of productivity growth than private research alone, although the impact of federally funded research is evidentially smaller. Further, some other studies have argued that the direct measured impact of federally supported R&D understates its true impact, because it generates additional funding of research by the private sector (Massofield, 1984). Some of this may originate in competition for federal research contracts. Lichtenberg (1986) finds extremely high spillovers from federal to private research during the period 1979-84.

These two definitions can be taken as parametric boundaries representing the upper and lower ranges for the R&D stock. In general, the lower bound is preferred. The exclusion of federally-funded research performed by private industry is likely to significantly underestimate investments for developing new technology.

Computing the R&D stock requires making initial assumptions regarding technical rather than physical depreciation, i.e., the obsolescence of prior knowledge as it is superseded by new research. The cumulative nature of scientific research suggests that R&D should not depreciate, and better empirical results are found for R&D as a determinant of productivity growth when zero depreciation is assumed (Terleckyj, 1983; Griliches, 1984; Griliches and Lichtenberg, 1984). On the other hand, microeconomic studies report high rates of depreciation for research within firms (Pakes and Schankerman, 1984). As pointed out in Sveikauskas (1981), conventional geometric rates of depreciation applied to R&D can yield zero or negative growth in technological advance. Detailed firm-level studies have been unable to ascertain the degree of depreciation of R&D (Griliches and Mairesse, 1984). Moreover, even when R&D spending depreciates within the firm, it may still contribute positively to the stock of technology for the industry or for the economy as a whole. For instance, Bernstein and Nodetc (1991) identify positive spillovers across industrial sectors from R&D spending. The implication is that use of a constant rate of depreciation will probably understated the true contribution of the stock of R&D spooling to the stock of technology. In the absence of definitive evidence as to the rate of technical depreciation, a zero rate is assumed.

IV. ESTIMATING THE PRODUCTION FUNCTION

The model is estimated using the factor shares method of Christensen, Jorgenson and Lau (1973), originally developed for translog specifications. Recall the notation used earlier. InF denotes the index of inputs. Competitive markets imply that the log marginal product of the input function with respect to the factors (lnF/lnX) equates to the input elasticities (αi/αX) and the marginal product multiplied by the factor shares of the inputs in total output (SF/αX)X/F). Further, cost-minimizing behavior implies that factor inputs converge toward cost shares, i.e., SF/lnX = PxF/PF. This implies that the input elasticities equal factor demand for X, denoted PX, where PX/F is total demand. In other words,

\[ \frac{F_{x}}{X_{x}} = \frac{\partial F}{\partial X_{x}} = \alpha_{x} \frac{X}{F} \Rightarrow \frac{\partial F}{\partial X_{x}} \frac{X}{F} > 0. \]

This yields the basic estimating equation for the input elasticities, Pxx/XY = nx/\mu_x. Research may involve long gestation periods before the effects on potential output are fully realized. Consequently, the R&D equation is not restricted to the contemporaneous value, but is estimated with distributed lags:

\[ P_{r,t} = \sum_{s=0}^{\infty} \alpha_{s} R_{t-s} + \mu_{t}. \]

By construction, \( \alpha_s = \alpha_r \). For the public sector capital stock, all terms in the user cost other than the dollar drop out. Distributed lags are unlikely to be applicable, since the use of infrastructure in normal economic activity is contemporaneous. On the assumption that the residual covariance matrix may contain non-zero off-diagonal elements, which would be the case if errors in cost-minimizing behavior are correlated across factor inputs, the efficiency of the estimates can be improved by iterative seemingly unrelated regressions ISUR, which is computationally equivalent to maximum-likelihood. Some writers have questioned the use of ISUR in production functions, arguing for an instrumental variables procedure on the grounds that the factor shares equations are potentially subject to simultaneous-equation bias. However, estimation by three-stage least squares (3SLS) would necessarily restrict the regressions to the contemporaneous value of the RHS variable, and would exclude lagged values, which are technically predetermined. Both methods are tested below. The choice between ISUR and 3SLS makes little difference for capital and labor, but as the sequel will demonstrate, distributed lag estimation yields significantly better results for the R&D equation. In this respect, the existing studies have indicated extended lags between R&D and growth in output or productivity. The lowest estimate is two years (Pakes and Schankerman, 1984), but other analyses have argued for considerably longer periods for basic research. The most common estimates have been in the range of three years for applied industrial research and five for basic (Lecy and Terleckyj, 1983).

In order to resolve the issues of lag length, each of the four factor shares equations (K,L,R,I) is estimated individually with the RHS in distributed lag form running up to five years, and a likelihood ratio test is applied. The Data

Output. Real output is gross private nonfarm output, measured in constant 1982 dollars. Total factor demand is output in current dollars. Despite the rebenchmarking of the national income accounts to 1987 dollars in 1992, constant 1982 dollars are preferred for two reasons. First, at the time of this writing, output in 1987 dollars is available only back to 1969, which prevents estimation of the production function for the mid-1980s, a period in which R&D was particularly significant. Second, the use of the 1987-weighted price index to compute real output may underestimate the capital stock, particularly the share of equipment investment comprised by computers. At the time of this writing, the Bureau of Economic Analysis (BEA) is working on alternative output
measures based on different price indexes, and until these are available 1982 dollars are used [BLS].

Labor. Labor is in manhours. To eliminate double counting, labor inputs are adjusted downward for the hours scientists and engineers spent in research [NSFP, 1992]. The cost of labor is the wage plus the employer share of social security taxes. Because total payments to labor include nonwage benefits in addition to indirect taxes, the resulting input elasticity should be viewed as conservative. However, there is insufficient data available on benefits to construct an estimate. [Bureau of Labor Statistics (BLS)]

Capital. The capital stock for private nonfarm output includes equipment, nonresidential structures and tenant-occupied residential buildings [Bureau of Economic Analysis (BEA)]. The cost of capital is the BLS rental price [BLS, 1983, 1991].

The public sector capital stock. The public sector capital stock includes all nonmilitary equipment and structures installed by the federal and state and local governments. The cost is the implicit deflator [BLS].

R&D. The broad measure of the R&D stock is defined as $\Sigma (R_1 + R_2 + R_{NL})$, only research performed by the federal government and federally funded nonprofits is excluded. The narrow measure is defined as $\Sigma (R_1 + R_2)$. All federally funded research is included, excluding research performed by industry. The cost of R&D for the broad definition is $R_1 + R_2 + R_{NL}$ where the $R$'s correspond to the weights of the three components in the R&D stock. The cost in the narrow definition is $R_1 + R_2$.

Table 1 presents preliminary ordinary least squares (OLS) estimates for the R&D equations and the likelihood ratio statistics for lag lengths of up to five years. The preferred lag structure is five and four years for the broad and narrow measures of the R&D stock (i.e., the contemporaneous value with four and three lags respectively). Preliminary regressions (not reported) estimated for the other factors favored contemporaneous values.

V. EMPIRICAL FINDINGS

Elasticities and Output Decomposition

The four-factor system was estimated using ISUR with distributed lags on R&D, and using 3SLS with contemporaneous values. Two lags of all the system variables were used as instruments in the first stage regressions. The likelihood ratio test statistics unambiguously favor the distributed lag specification. The input elasticities for the broad definition are $\alpha_0 = 0.6351$, $\alpha_1 = 0.2181$, $\alpha_2 = 0.0890$, $\alpha_3 = 0.0849$. Returns to scale in the input function are marginally increasing: 1.0381. In a two-factor model, returns to scale would be sharply decreasing, a result also found in Bokin and Lee (1991). The factor-shares equations estimated for the narrow measure of the R&D stock yield elasticities of $\alpha_0 = 0.6359$, $\alpha_1 = 0.2194$, $\alpha_2 = 0.0799$, $\alpha_3 = 0.0639$, summing to 0.9912. The elasticities can be used to decompose the growth rate of aggregate output into its supply-side constituents. Table 2 presents this analysis for the period 1950-90 (the analysis begins in 1955 in order to avoid starting in a recession year). Of the 3.25 percent growth in output, the contributions of labor, private and public capital are 1.25, 0.72 and 0.22 respectively. The contributions of technological advance using the broad and narrow measures of the R&D stock are 0.39 and 0.71 respectively, yielding residuals of 0.11 and 0.35, much smaller than in the standard two-factor framework. The
combined contribution of labor and capital is significantly lower than in the BLS decomposition. The reason is that here the input elasticities are estimated freely, whereas the BLS constrains the coefficients on K, L to sum to unity. The implication is that the CRTS restriction used in the BLS decomposition overstates the true contribution of the factor inputs and underestimates multifactor productivity, or technological advance. This conclusion is not contingent on the use of the R&D stock to represent technological advance, but rather only on the relaxation of the CRTS restriction.

### Time-Varying Parameter Estimates

It is also of interest to decompose output by its supply constituents over individual business cycles. The elasticities estimated over the full period should in principle not be used for this purpose, however, since they include observations that postdate the actual cycles. For this reason, the input elasticities are reestimated using time-varying parameter regressions, calculated from a Kalman filter algorithm. The time-varying coefficients are shown in Appendix 1. The input elasticity for capital peaks in the early 1960s, and then declines steadily. The labor elasticity exhibits irregular fluctuations, with successive peaks. The elasticity for public capital exhibits two cycles. The R&D elasticity declines continuously until 1970, and then increases until 1990. The mean values of the elasticities are \( \alpha_r = 0.0457 \), \( \alpha_L = 0.0297 \), \( \alpha_C = 0.0610 \), and \( \alpha_K = 0.0847 \) using the broad definition and \( \alpha_r = 0.0634 \) using the narrow definition. Combined returns to scale are a bit higher using the time-varying elasticities, but still within the same order of magnitude as the fixed-parameter estimates.

The results from the time-varying regressions for the full period are presented in Table 2. Table 2 shows the decomposition of output for five shorter periods. The unusual cyclical volatility of the economy during the period 1955-60 (two recoveries, two recessions) coupled with rapid increases in R&D makes it impossible to carry out the decomposition without large residuals. However, if 1955-60 is treated as a single period, the decomposition yields plausible results, although this interval technically spans three cycles. The reasons for the difference between the output residual using the broad and narrow measures of the R&D stock are evident from Table 1. R&D financed by the federal government but performed by private industry grew unusually rapidly during the 1950s, causing the output residual to be slightly negative when the stock of technology is broadly defined. An additional decomposition is provided for the simple cycle in 1960-69. Here, there is a positive output residual, which may be explained by the effects of the Vietnam War escalation. In 1969-73, the residual is virtually eliminated. Any positive effects on output from wage-price controls seem to have been offset by other factors, conceivably the rise in commodity prices due to intensity of worldwide demand, which lower the output residual by raising the cost of intermediates. The effect of the OPEC price shocks, which raised the cost of energy inputs and other energy-using intermediates, is visible in the negative output residual recorded for 1973-79. There is a small positive output residual (0.24 to 0.29) in the period 1978-90, which may be attributable to increasing efficiencies in the use of intermediate inputs, but also reflects the simultaneous slowdown in the stocks of private and public capital and R&D spending.

### Factor Augmentation

The time-varying input elasticities make it possible to investigate in a new way whether technology should be viewed as neutral or factor-augmenting. Labor and capital augmentation can be tested as competing hypotheses using the term \( \frac{\partial \ln Y}{\partial \ln K} / \frac{\partial \ln F}{\partial \ln L} \), which from Equation 7 equates conceptually to the capital-labor ratio \( c_L / c_K \). In previous studies, factor augmentation has frequently been estimated by a simple regression on time; however, this ratio may evolve over time for reasons unrelated to technology. Instead, to test the role of technology in factor...
Decomposition of Output by Factor Input, Individual Business Cycles

The four-factor production function approach has yielded several findings. First, by using the R&D stock as a factor input, we have been able to replicate the standard decomposition into labor productivity and the other three factors. More importantly, by estimating the returns to each factor, we find that the R&D stock is the most significant factor. In our estimation, the labor productivity component is estimated to be approximately 90% of the total productivity difference. Both the marginal labor productivity and R&D inputs were estimated by using the Augmented Output Function Approach (AOF). The results indicate that the marginal labor productivity is the most significant factor in explaining the productivity difference. The R&D stock is also found to be significantly different from zero, while the product of labor productivity and R&D inputs is found to be significantly different from zero. The results also show that the marginal labor productivity is the most significant factor in explaining the productivity difference.

The results of our decomposition are consistent with the findings of previous studies. The productivity difference is found to be significant, and the R&D stock is found to be the most significant factor in explaining this difference. The results also suggest that the productivity difference is not only due to the product of labor productivity and R&D inputs, but also due to the marginal labor productivity. The results also indicate that the marginal labor productivity is the most significant factor in explaining the productivity difference. The R&D stock is also found to be significantly different from zero, while the product of labor productivity and R&D inputs is found to be significantly different from zero. The results also show that the marginal labor productivity is the most significant factor in explaining the productivity difference.

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APPENDIX I

Time Varying Elasticities

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TECHNICAL ADVANCE

NOTES

The conclusions in this paper are those of the author alone, and do not necessarily reflect the policy position of the National Association of Manufacturers. The author acknowledges the support of the National Science Foundation. The author acknowledges his assistance in the research. The author acknowledges the support of the National Science Foundation.

1. Two measures of embedded technological advances, capital quality (approximated by different vintages of equipment) and labor force skills (quality based on education levels) are analyzed by Leonardo (1989). For the period 1977-83, private nonfarm output growth of 0.28 percent per year shows a total effect for capital of 1.46 percent per year, with 0.68 attributed to the growth of the capital stock and 0.88 attributed by the model. The total effect of labor is 1.12, with 0.73 increasing in labor hours contributing 0.73, and skills contributing 0.39. The residual in this decomposition is 0.71, considerably less than in the standard two-factor approach. It should be noted here that the combined impact of labor force quality and labor hours worked is within the range defined by standard estimates of labor inputs, and similar to the findings to this paper. In other words, disaggregating labor force quality from total labor inputs does not match the residual output, but leaves the magnitude of the total labor effect unchanged.

2. As written, the production function imposes a zero restriction on any second-order effects. This is somewhat arbitrary, and as a result it may be more to estimate the model in translog form, derived from a second-order Taylor series approximation around the inputs (Christensen, Jorgenson and Lau, 1979; Herr and Khalid, 1977). The second-order translog function is defined as:

\[ \ln Y = a_0 + a_1 L_n + a_2 K_n + a_3 L K_n + a_4 L^n + a_5 K^n + a_6 L^2 + a_7 K^2 + a_8 L K^2 + a_9 L^2 K + a_{10} L K^2 + a_{11} L^2 K^2 + a_{12} L^3 + a_{13} K^3 + a_{14} L^3 K + a_{15} L^2 K^2 + a_{16} L K^3 + a_{17} K^4 + a_{18} L^2 K^2 + a_{19} L K^3 + a_{20} K^4 \]

Estimating the translog by factor shares however requires imposing a series of cross-equation restrictions on the second-order terms. As the sequel will demonstrate, these restrictions are not supported empirically. Consequently, the estimations will be on the results from equation (4).

3. The statistical properties of the R&D data are dissimilar in several respects from measures of aggregate output. While most aggregate production series are R1 or R2 stationary for the postwar period, the R&D data is not. Rather than apply conventional unit root tests which distinguish only between R1 and R2 series, the Geweke-Porter-HAPSHOT test (1988) for fractional integration was used. This test is a frequency domain regression designed to identify the dominant root (which may be less than unity) by regressing the periodogram of the harmonic estimates on the spectral density function. The estimated values for the degree of integration were: R1 = 0.59, R2 = 0.66, R1 = 0.64, R2 = 0.66. While the standard errors in these regressions is relatively large (0.68), only industrial R&D appears to be a unit root series. Furthermore, tests below unity but above the threshold for stationarity (0.65) can be accounted for by high degrees of inertia in time series, but are also consistent with deterministic in long-term rates of change.

7. A significant value therefore rejects the restrictions and favors the larger lag structure.

8. The corresponding equations for the translog form require entering the second-order terms on the RHS, which eliminates the distributional lag assumption.

9. In the substitute equations, the translog requires that a_2 = a_4 = a_6 = a_8 = a_10 = a_12 = a_14 = a_{16} = a_{18} = a_{20} = 0. These restrictions can be tested by direct estimation and by F-tests in the constraints. When estimated freely, the translog equations overwhelmingly reject the implied restrictions. When either BEW or BLW estimation is used, the selected algorithm overturns the second-order terms to differ.
REFERENCES


