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THE SOURCES OF LABOR PRODUCTIVITY VARIATION IN U.S. MANUFACTURING, 1947-80

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Abstract

Because it concentrates on the co-movements of jointly determined endogenous variables, the traditional analysis of labor productivity does not directly address the question of the causes of productivity change. This problem is solved by a modelling approach in which productivity and other choice variables are assumed to respond optimally to five broad classes of exogenous (causal) shocks. Although these shocks are unobservable to the econometrician, maximum likelihood estimates of their relative importance in the determination of productivity change are obtained.

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1. Introduction

Much effort has been expended in attempts to account empirically for changes in measured labor productivity (hereafter, simply "productivity"), especially the changes that have taken place in the U.S. since 1973. Denison's survey (1979) cites literally dozens of relevant studies. Despite all this research, there is surprisingly little agreement about the sources of productivity variation. The purpose of this paper is to suggest that the bar to greater understanding is partly methodological in origin and to demonstrate an alternative approach to the analysis of productivity.

A standard procedure for studying productivity and growth (introduced by Denison (1974) but used by others) is the method of "growth accounting." Broadly, growth accounting is a way of decomposing economic growth (or its per-capita counterpart, productivity) into its major "sources": notably, increases in 1) the quality and quantity of capital inputs, 2) the quality and quantity of labor inputs, and 3) various "residual" factors. These characterizations of the sources of growth have been widely influential.

A problem arises, however, when one asks, "In what sense does growth accounting elucidate the <u>causes</u> of growth or productivity increase?" The usual notion of "causality" is of a link between exogenous (causal) variables on the one hand, and endogenous (caused) variables on the other. Yet in standard economic analysis the levels of capital and labor inputs (growth accounting's principal "source" variables) are thought of as <u>jointly endogenous</u>

with productivity within the economic system. Thus one does not usually speak of capital or labor growth as "causing" productivity change; rather, all three variables are chosen together in light of the economic environment.

This methodological point becomes practically important when one attempts to apply research results to policy formulation. Because growth accounting is not a causal analysis, its policy implications are typically ambiguous. For example, suppose that this method reports that a productivity slowdown is associated primarily with a reduction in the growth rate of the capital stock. The appropriate policy response to this information depends on the nature of the exogenous change that affected the two endogenous variables (capital and productivity). A joint slowdown of productivity and capital growth could be caused by an inflation-induced increase in the burden of taxation on capital; by a reduced rate of labor-saving innovation; by demographic shifts in the labor force; or by a lower level of output demand, to name a few possibilities. Optimal policy (including the option of doing nothing) would vary over these cases.

This paper re-addresses the question of productivity determination with techniques that solve the "joint endogeneity" problem and employ a sound notion of causality. The specific object of study is productivity in the U.S. manufacturing sector in the postwar (1947-80). We use a modelling approach which recognizes explicitly that measured productivity levels are not a "given" to the manufacturing sector but represent choices made by workers and firms in response to exogenous constraints. Production and input levels are assumed to be varied optimally in the face of five broad classes of externally generated "shocks". Looking at production, prices, wages, capital, and labor inputs as well as productivity, we can associate different response patterns with each type of shock.

The fact that different types of unobservable shocks create different patterns in the data is used to measure the relative importance of each class of shocks for productivity. The key pieces of information are the variances and covariances of the observables. Roughly, the type of inference made is as follows: Suppose that a shock of type a leads to movements of variables x and y in the same direction, while the optimal response to a shock of type b gives the changes in x and in y opposite signs. Then if we observe (for example) a large positive sample covariance of x and y, we will tend to infer, using this method, that type a shocks were more important historically than the type b variety.

A finding of this paper is that the largest sources of productivity change are 1) factors that directly affect the sector's production possibilities, e.g., technology, and 2) the costs of capital, including utilization costs. Variations in product demand, labor supply, and cyclical influences are found to be relatively less important.

2. A Model of the Response of Productivity to Exogenous Shocks

This section presents a simple partial equilibrium model of the manufacturing sector. Our purposes are to analyze the response of productivity and other endogenous variables to certain types of exogenous shocks and to provide a basis for the empirical work described later.

The specification of the model begins with three equations:

(1) Product demand

$$Q_t = \eta^d P_t + X_t^d$$

(2) Production function

$$Q_t = X_t^q + \alpha_n N_t + \alpha_k K_t + U_t$$

(3) Labor supply

$$N_t^s = \eta^s W_t + X_t^n$$

where

Q_t = log of manufacturing output (in period t)

P_t = log of the relative price of manufactured goods

N_t = log of labor input to manufacturing

K_t = log of capital input to manufacturing

W_t = log of manufacturing real wage

For a given period t, the product demand equation relates purchase of manufacturing output (measured in real terms) to the sectoral relative price.[1] Since production and prices are measured in logs, η^d represents the price-elasticity of demand. Assuming a downward-sloping demand function, we take $\eta^d < 0$. X_t^d is the current level of the demand function intercept; it captures non-price determinants of demand such as national income, tastes, and alternative opportunities of consumers. X_t^d will be assumed to evolve stochastically over time; see below.

The production function is ordinary Cobb-Douglas with exponents α_n and α_k, corresponding to labor's and capital's share, respectively. We assume constant returns to scale, so that $\alpha_n + \alpha_k = 1$. X_t^q, assumed stochastic, is the (log of) the Cobb-Douglas "technical progress" index; it is the capacity of firms to produce, given measured levels of inputs. Because of familiar problems of measurement of inputs and output, in our estimates X_t^q will include such factors as input quality variations and the impact of government regulation on marketed output as well as technical and managerial efficiency.

The U_t term in the production of function is the average level of factor utilization intensity in period t. It is a choice variable, not a stochastic disturbance. (Random disturbances to production are subsumed in X_t^q.) Varying U_t allows firms to produce "off of" the production function for a time by working labor and machines at a faster or slower rate. Firms are assumed to aim for a long-run "normal" utilization rate $U = 0$ and to balance upward against downward deviations from this norm.

The <u>labor supply equation</u> gives the number of labor hours offered to the manufacturing sector as a function of the real wage paid in that sector. η^s, the wage-elasticity, will be assumed positive. The stochastic intercept term X_t^n summarizes current levels of non-wage influences on labor supply, such as population, income, and wealth, as well as the alternative opportunities of workers in other sectors, self-enployment, or non-work pursuits.

To complete the basic model, we assume that the unit rental and utilization cost of capital is exogenous and given by X_t^k. X_t^k is stochastic and includes, for example, the energy costs of running a machine, as well as more conventional capital costs such as interest and depreciation.[2]

Suppose for the time being that there are no adjustment costs associated with changing input stocks. Then, competitive profit-maximization and the basic model imply[3]

(4) Pricing equation

$$P_t = - X_t^q + \alpha_n W_t + \alpha_k X_t^k + \text{constant}$$

(5) Labor demand

$$N_t^d = - X_t^q + \alpha_k (\log(\alpha_n/\alpha_k) + X_t^k - W_t) + Q_t$$

(6) Capital demand

$$K_t^d = - X_t^q + \alpha_n(\log(\alpha_k/\alpha_n) + W_t - X_t^k) + Q_t$$

The pricing equation states that, with constant returns to scale, prices must equal costs of production. The conditional factor demand equations give total input usage as a function of relative factor costs and desired production levels. Note that an increase in the production function intercept, X_t^q, lowers input requirements per unit output and thus reduces prices.

The dynamics of this model depend on the evolution of the stochastic variables X_t^d, X_t^q, X_t^n, and X_t^k. A descriptive and quite general specification breaks each variable into three parts: 1) a deterministic time trend; 2) a component in which all changes are permanent (a "random walk"); and 3) a component in which all changes are transitory (so that the level of the component always tends towards a fixed mean). Thus we might write

(7) $$X_t^i = \bar{X}_t^i + Y_t^i + \delta^i t$$

where

(8) $$\bar{X}_t^i = \bar{X}_{t-1}^i + \varepsilon_t^i$$

Y_t^i = the current value of a mean-zero stationary process

$i = d,q,n,k$

The δ^i are constants, and the ε_t^i are independent normal shocks with means zero and variances σ_i^2.

A specification in the form of (7) will be used in the estimation reported below. For the rest of this section, however, we will consider only an important special case of (7). This is the case in which $Y_t^i = 0$, all i and t; that is, all shocks to the X_t^i are taken to be permanent in nature. We also assume that all variables have been detrended in order to avoid having to carry along terms in δ^i in our calculations.

Let $(q_t^*, p_t^*, w_t^*, n_t^*, k_t^*)$ denote the first differences of $(Q_t, P_t, W_t, N_t, K_t)$ in a model in which there are only permanent shocks. These starred lower-case variables can be thought of as <u>desired growth rates</u>, less trend. If supplies and demands are equal in factor and product markets, the five desired growth rates satisfy the five-equation system given in Table 1. (Equations 3 and 4 in Table 1 are market-clearing conditions for labor and capital, respectively; equation 5 follows from the constancy of factor shares in the Cobb-Douglas technology.) The stochastic terms ε_t^i are, recall, the current innovations to the random walk processes $\bar{X}_t^i$ (i = d,q,n,k).

A reduced-form solution of the system in Table 1 gives expressions for the desired growth rates in terms of the disturbances ε_t^i. (This solution is given in the Appendix.) Table 2 gives the derivatives of the desired growth rates with respect to each type of shock:

1) A positive shock to demand raises production and prices. The induced increase in factor demands raises wages and both factor inputs.

2) A favorable technology innovation lowers prices and therefore increases output demanded. If demand is relatively elastic ($\eta^d < -1$), the increase in demand will offset the lower per-unit factor requirements, raising factor inputs and wages.

3) A positive labor supply innovation increases labor input and lowers wages. Lower wages lead to lower prices and more demand. If demand is sufficiently elastic, more capital inputs will be required.

4) An increase in capital costs lowers capital input, raises prices, and lowers output demanded. If demand is elastic, the output fall will be large enough to reduce labor input and wages as well.

This model can be used to analyze the effects of external shocks on the desired growth rate of productivity, $q^* - n^*$:

1) A positive shock to product demand increases productivity. Because capital is supplied more elastically than labor in the long run, the higher level of production takes place on a more capital-intensive basis than before. This long-run effect is independent of cyclical variations in productivity, which are due to the impact of temporary demand shifts on input utilization rates.

2) An improvement in the production function raises productivity, both directly and through expansion of output demanded.

3) A positive change in labor supply reduces productivity by inducing substitution toward labor inputs and away from capital inputs.

4) Similarly, an increase in capital costs reduces productivity by inducing a substitution toward labor.

Most of the important influences that permanently shift the level of labor productivity can be classed as one of the four types of exogenous influences or "shocks" of this simple model. It will be useful to know roughly how much of productivity variation is attributable to each of these long-run factors, as well as to short-run influences such as the business cycle. This decomposition is the goal of the empirical analysis of this paper.

Table 1

LOG-DIFFERENCE FORM OF THE THEORETICAL MODEL, EXCLUDING TRANSITORY SHOCKS

(1) $q_t^* = \eta^d p_t^* + \varepsilon_t^d$

(2) $p_t^* = -\varepsilon_t^q + \alpha_n w_t^* + \alpha_k \varepsilon_t^k$

(3) $-\varepsilon_t^q + \alpha_k(\varepsilon_t^k - w_t^*) + q_t^* = \eta^s w_t^* + \varepsilon_t^n$

(4) $-\varepsilon_t^q + \alpha_n(w_t^* - \varepsilon_t^k) + q_t^* = k_t^*$

(5) $q_t^* + p_t^* = w_t^* + n_t^*$

Table 2

DIRECTION OF RESPONSE OF ENDOGENOUS VARIABLES TO SHOCKS

	ε^d	ε^q	ε^n	ε^k
q*	+	+	+	-
p*	+	-	-	+
w*	+	+ (if $\eta^d < -1$) - (if $\eta^d > -1$)	-	- (if $\eta^d < -1$) + (if $\eta^d > -1$)
n*	+	+ (if $\eta^d < -1$) - (if $\eta^d > -1$)	+	- (if $\eta^d < -1$) + (if $\eta^d > -1$)
k*	+	+ (if $\eta^d < -1$) - (if $\eta^d > -1$)	+ (if $\eta^d < -1$) - (if $\eta^d > -1$)	-
q*-n*	+	+	-	-

3. Econometric Approach

If the desired growth rates $v^* = (q^*, p^*, w^*, n^*, k^*)$ could be observed, then a number of attractive strategies for determining the sources of productivity variation in the data would be available. One possibility would be to use the distinct sign patterns created by different types of shocks (see Table 2) to segregate the causes of productivity change. This approach would have the virtue of being largely independent of specific estimates of incidental parameters. Or, if one were willing to estimate or otherwise specify parameter values, inversion of the system in Table 1 would allow direct calculation of the magnitude of each shock in each period.

Unfortunately, it is unlikely that actually observed detrended growth rates, denoted by $v = (q, p, w, n, k)$, will be good proxies for their "desired" counterparts v^*. While the elements of v^* must by assumption be serially uncorrelated, the observable vector v displays, in practice, distinct serial correlation patterns. These serial correlation patterns are created by the persistence of cyclical components and by the fact that adjustment of actual variables v to desired levels v^* within a year may be incomplete. Thus our approach will be to treat the desired growth rates v^*, as well as an additional cyclical variable, as <u>unobserved</u> components of the vector v. A generalized form of factor analysis can then be used to extract estimates of the key variances and the parameters.

More explicitly, we will consider representations of the observable variables of the form

$$
(9) \qquad
\begin{aligned}
q_t &= b_q(L)\, q_t^* + y_t \\
p_t &= b_p(L)\, p_t^* + c_p(L)\, y_t \\
w_t &= b_w(L)\, w_t^* + c_w(L)\, y_t \\
n_t &= b_n(L)\, n_t^* + c_n(L)\, y_t \\
k_t &= b_k(L)\, k_t^* + c_k(L)\, y_t
\end{aligned}
$$

where y_t is a stationary ARMA process with normally distributed innovations, and the $b_i(L)$ and $c_i(L)$ are general lag polynomials. The import of this specification is that each observed growth rate is taken to be the sum of two components: 1) a gradual adjustment to the corresponding desired growth rate[4] and 2) a transitory or "cyclical" element, represented by a distributed lag on the unobservable process y. The process y is intended to capture effects of the business cycle; but it can include other transitory impacts on growth rates, such as wars. Notice that we have assumed that only one independent transitory process affects all five variables; this prior restriction improves the degree of econometric identification greatly. We have not imposed cross-restrictions on the lag polynomials. Thus we do not require, for example, that the relation of production to inputs in the short run be given by the long-run production function. This potential inconsistency is removed by the realistic assumption that the average utilization rate U_t can vary in the short run.

The desired growth rates v* are linear combinations of the normally distributed, mean-zero, permanent shocks $\varepsilon^* = (\varepsilon^d, \varepsilon^q, \varepsilon^n, \varepsilon^k)$; thus v* is itself multivariate normal with zero mean. The transitory process y can similarly be expressed as a linear combination of its normal innovations ε^y.

Finally, the observed variables v are linear transformations of v* and y. Thus, if we let h denote a vector of all observations of the vector v, h will be multivariate normal itself. The mean of h will be zero and its covariance matrix will be $\Omega(\theta)$, where θ is a vector of the unknown parameters. The unknown parameters in θ include the variances of the unobservable shocks ε^* and ε^y; the parameters of the model in Table 1, which relate v* to ε^*; the coefficients of the lag polynomials in (8) above; and the parameters of the ARMA process describing y. The log-likelihood of the sample is

$$\text{(10)} \qquad L = -1/2 \log \det \Omega(\theta) - 1/2\, h' \,\Omega(\theta)^{-1} h$$

plus an inessential constant. The values of the parameters in θ which maximize L have the usual consistency and efficiency properties of ML estimates.

This estimation procedure has a relatively simple intuitive description. For any choice of the unknown parameters θ one can calculate an implied variance matrix $\Omega(\theta)$ for the observed data h. The maximum likelihood estimates of θ are those which imply the matrix $\Omega(\theta)$ most closely matched to the variances and covariances of the actual sample.

The estimates reported in this paper were obtained by use of a program written by Bronwyn Hall. The program, described in B.H. Hall (1979), employs analytic derivatives and the method of scoring.

For an early application of this econometric methodology, see Chamberlain and Griliches (1975). The present paper owes a great deal to a similar variance decomposition exercise by R.E. Hall (1978), in which the sources of macroeconomic fluctuations were analyzed.

4. Data

The data used in the empirical analysis are as follows:

1. Q: Index of industrial production, manufacturing; Survey of Current Business

2. P: Wholesale price index, manufactured goods, June of each year; adjusted for seasonal variation and deflated by the PCE implicit price deflator; SCB

3. W: Average hourly gross earnings per production worker on manufacturing payroll; deflated by the PCE implicit price deflator; SCB

4. N: Index of aggregate weekly employee hours, production workers; SCB

5. K: Fixed nonresidential business capital, constant cost valuation, 1972 dollars, manufacturing; equipment and structures; from Bureau of Economic Analysis, Fixed Nonresidential Business and Residential Capital in the United States 1929-75, and SCB updates.

All data are annual. Coverage is from 1947 to 1980. The log-differenced and detrended forms of the above data, denoted by lower-case letters, are given in Table 3. To illustrate the interpretation of the numbers in Table 3, note that the value for q in 1948 was -.0025; this tells us that between 1947 and 1948 production grew at a rate of 0.25% below the postwar trend.

The last column of Table 3 reports the detrended growth rate of labor productivity (output per production worker hour). This column confirms the usual observation that recent productivity growth has been weak: Productivity growth was below the postwar trend in every year from 1973 to 1980 except 1976. Another observation is that the annual nature of the data and the use of hours as a measure of labor input all but eliminate the cyclical aspect of productivity. For example,

Table 3. LOG-DIFFERENCED AND DETRENDED DATA, 1948-80

	q	p	w	n	k	q-n
1948	-.0025	-.0328	.0144	-.0181	.0508	.0156
1949	-.0952	-.0362	.0247	-.1153	.0019	.0201
1950	.1109	-.0046	.0087	.0911	-.0068	.0198
1951	.0371	.0701	.0011	.0672	.0162	-.0301
1952	.0004	-.0538	.0174	-.0024	.0080	-.0020
1953	.0453	-.0212	.0181	.0445	.0023	.0008
1954	-.1075	-.0005	-.0010	-.1168	.0005	.0093
1955	.0824	-.0032	.0188	.0596	-.0020	.0228
1956	-.0011	.0200	.0114	.0018	.0154	-.0029
1957	-.0284	-.0017	.0027	-.0351	.0105	.0067
1958	-.1110	-.0109	-.0089	-.1133	-.0205	.0023
1959	.0791	-.0078	.0028	.0736	-.0310	.0055
1960	-.0214	-.0191	-.0026	-.0174	.0220	-.0040
1961	-.0368	-.0204	-.0007	-.0403	-.0265	.0034
1962	.0462	-.0137	-.0011	.0435	-.0236	.0027
1963	-.0082	-.0135	-.0018	.0056	-.0171	-.0138
1964	.0532	-.0141	-.0010	.0213	-.0044	.0319
1965	.0621	.0018	-.0030	.0592	.0203	.0029
1966	.0476	-.0044	-.0026	.0635	.0370	-.0159
1967	-.0187	-.0166	-.0011	-.0203	.0305	.0016
1968	.0221	-.0149	.0061	.0154	.0113	.0067
1969	.0024	-.0094	-.0028	.0122	.0086	-.0098
1970	-.0822	-.0108	-.0081	-.0737	-.0056	-.0085

	q	p	w	n	k	q-n
1971	-.0231	-.0093	.0015	-.0417	-.0220	.0186
1972	.0544	-.0025	.0147	.0512	-.0184	.0032
1973	.0478	.0444	-.0009	.0562	-.0020	-.0084
1974	.0430	.0492	-.0406	-.0299	.0023	-.0131
1975	-.1466	.0363	-.0079	-.1282	-.0265	-.0184
1976	.0676	-.0028	.0094	.0566	-.0070	.0110
1977	.0266	.0104	.0189	.0371	-.0009	-.0105
1978	.0190	.0027	.0029	.0434	.0042	-.0244
1979	.0054	.0172	-.0198	.0159	.0036	-.0105
1980	-.0838	.0065	-.0697	-.0667	.0131	-.0171

productivity growth was above trend in the severe recession year 1958; and 1975 had no worse productivity performance than some other recent years.

For the purposes of our estimation the moment matrix of the data captures all usable information. The raw sample covariances (which the estimation procedure will try to "match") are given in Table 4.

Table 4

SAMPLE COVARIANCES, 1947-80

	q_t	p_t	w_t	n_t	k_t
q_t	.3785				
p_t	-.0001	.0594			
w_t	.0402	-.0130	.0300		
n_t	.3600	.0161	.0296	.3613	
k_t	.0124	.0010	.0000	.0150	.0348
q_{t-1}	-.0747				
p_{t-1}	-.0548	.0055			
w_{t-1}	.0237	-.0021	.0089		
n_{t-1}	-.0982	.0335	-.0223	.0150	
k_{t-1}	-.0390	-.0104	.0024	-.0406	.0181
q_{t-2}	-.0792				
p_{t-2}	.0082	-.0028			
w_{t-2}	-.0118	.0071	-.0037		
n_{t-2}	-.0801	-.0461	-.0221	-.0952	
k_{t-2}	.0039	-.0058	.0022	-.0010	.0063

Note: Data are multiplied by 100 for notational compactness.

5. Results of the Estimation

The estimation procedure required the numerical maximization of a likelihood function with respect to the vector of free parameters. Keeping computer costs down and, indeed, achieving a solution required the list of estimated parameters to be as short as possible. Accordingly, we looked for specifications that would be parsimonious without being inflexible. We also assumed

$$\alpha_k = .30$$
$$\alpha_n = .70$$

These are conventional values for the Cobb-Douglas exponents.

Given the prior restrictions, a number of simple variants of the general specification provided reasonable and largely identical results. A representative model is given in Table 5; corresponding estimates are reported in Table 6. Note that, despite parsimonious specification and some pre-testing to eliminate extraneous parameters, estimation of this model required maximization of the likelihood function with respect to nineteen free parameters. Nineteen is a large number for this sort of procedure.

The key results of this exercise are the estimates of the variances of the different types of unobservable shocks (parameters 1-5). Presentation of these we leave to the next section. Here we briefly examine the implications of the estimates of the remaining fourteen parameters.

Table 5

SPECIFICATION OF ESTIMATED MODEL

1) $q_t = q_t^* + y_t$

2) $p_t = \mu_p p_t^* + \lambda_p (1-\mu_p) p_{t-1}^* + \lambda_p (1-\lambda_p)(1-\mu_p) p_{t-2}^* + \beta_p y_{t-1}$

3) $w_t = \mu_w w_t^* + \lambda_w (1-\mu_w) w_{t-1}^* + \lambda_w (1-\lambda_w)(1-\mu_w) w_{t-2}^* + \beta_w y_{t-1}$

4) $n_t = n_t^* + \beta_n y_t$

5) $k_t = \mu_k k_t^* + \lambda_k (1-\mu_k) k_{t-1}^* + \lambda_k (1-\lambda_k)(1-\mu_k) k_{t-2}^* + \beta_k y_{t-1}$

6) $y_t = \rho_1 y_{t-1} + \rho_2 y_{t-2} + \varepsilon_t^y$

Table 6

PARAMETER ESTIMATES

	Parameter	Estimate (t-statistic)	Parameter Definition
1.	σ_d^2	.003731 (6.61)	Variance of product demand shocks
2.	σ_q^2	.000210 (4.68)	Variance of production function shocks
3.	σ_n^2	.015900 (1.87)	Variance of labor supply shocks
4.	σ_k^2	.001613 (3.95)	Variance of capital cost shocks
5.	σ_y^2	.000365 (1.97)	Variance of cyclical shocks
6.	μ_p	.800 (8.13)	First-year adjustment of prices to permanent shocks
7.	λ_p	-.054 (-0.14)	Subsequent-year rate of price adjustment
8.	β_p	.814 (3.69)	Response of prices to (lagged) cycle
9.	μ_w	.562 (3.57)	First-year adjustment of real wages to permanent shocks
10.	λ_w	.598 (1.64)	Subsequent-year rate of real wage adjustment
11.	β_w	-.624 (-3.87)	Response of real wages to (lagged) cycle
12.	β_n	.859 (8.61)	Response of labor hours to cycle
13.	μ_k	.167 (9.56)	First-year adjustment of capital stock to permanent shocks

Table 6 (Cont'd)

	Parameter	Estimate (t-statistic)	Parameter Definition
14.	λ_k	.269 (10.83)	Subsequent-year rate of capital stock adjustment
15.	β_k	.373 (4.70)	Response of capital stock to (lagged) cycle
16.	ρ_1	.098 (0.69)	Parameters of (AR2) cyclical process
17.	ρ_2	-.394 (-2.78)	
18.	η^d	-.340 (-1.02)	Price-elasticity of demand for output
19.	η^s	7.07 (3.12)	Wage-elasticity of supply of labor

Nearly all of these other parameters were introduced to describe the dynamics of the observed variables. Recall from (9) that the dynamic behavior of the observed variables was modelled as being comprised of two parts: 1) a gradual adjustment of the actual growth rates v to the long-run desired rates v*, and 2) a response to cyclical or other transitory forces. There are five of these growth rates to be considered - production, prices, wages, labor, and capital.

The growth rates of production and of labor input were highly correlated and thus can be looked at together. For neither variable could our preliminary tests reject the hypothesis that complete adaptation to change in long-run desired growth rates occurs within the first year; this was imposed in the reported estimates. The non-zero serial correlation of production and labor growth is therefore explained entirely by cyclical influences. The cyclical component of output (identical to the unobservable process y) was modelled as AR(2), with estimated parameters $\hat{\rho}_1 = .098$ and $\hat{\rho}_2 = -.394$.[5] Labor input (measured as hours) was found to be sensitive to the output cycle. The estimate of β_n implies that a 1% temporary increase is production is associated with a 0.86% increase in labor hours. Since the response of labor input to output fluctuations is less than one-for-one, high points in the business cycle are associated with above-normal utilization rates and corresponding temporary increases in productivity. As noted previously, however in these data the cyclical effect on productivity is small (and, indeed $\hat{\beta}_n$ is close to one.)

Manufacturing relative prices also are seen to adjust rapidly to changes in long-run desired levels. The response of prices in the first year to permanent shocks is estimated to be 80% ($\hat{\mu}_p$). The subsequent rate of adjustment to permanent shocks ($\hat{\lambda}_p$) could not be pinpointed; the actual estimate is small negative but the standard error is very large. Prices are fairly responsive to transitory influences as well; a temporary 1% expansion in manufacturing output leads the next year to a 0.82% ($\hat{\beta}_p$) increase in relative prices. The fact that the relative price response is this large suggests that transient shocks specific to the manufacturing sector are not insignificant in comparison to aggregate business cycle shocks.

As might be expected, the adjustment of real wage growth to desired long-run rates is more sluggish. The estimate of first-year real wage adjustment ($\hat{\mu}_w$) is 56.2%; the gap is closed at a rate of 59.8% ($\hat{\lambda}_w$) in subsequent years. Thus a unit shock to the desired rate of real wage growth leads to the following cumulative wage growth response in the first four years:

1	2	3	4
.562	.823	.929	.971

Interestingly, the response of real wages to transitory output variations is negative: A temporary 1% increase in output leads to a 0.62% drop ($\hat{\beta}_w$) in real wages the next year. This result seemed quite robust to different specifications; it may have arisen because nominal wages are less responsive in the short run than are prices.

The estimated model also provides information about the rate of capital stock adjustment. Only 16.7% ($\hat{\mu}_k$) of an unanticipated change in the manufacturing sector's long-run desired capital stock can be made up in the first year, with 26.9% ($\hat{\lambda}_k$) of the remaining gap filled in each subsequent year. This leads to the following six-year cumulative response pattern:

1	2	3	4	5	6
.167	.391	.555	.675	.762	.826

These estimated investment lags are somewhat longer than those found by more conventional methods. This slow-adjustment result should not, however, be dismissed: We would point, first, to the very low standard errors of the estimates of μ_k and λ_k; and, second, to the fact that our method does not suffer the simultaneity problems common to many investment studies. Investment also reacts positively to transitory increases in output: A 1% temporary expansion of production is associated with a 0.37% ($\hat{\beta}_k$) increase in investment the following year.

The last two parameters for which estimates are reported are the price-elasticity of demand for manufacturing output (η^d) and the wage-elasticity of the supply of labor to the manufacturing sector (η^s). The value of $\hat{\eta}^d$ is a plausible -0.34. The estimate of 7.07 for η^s seems too high until one remembers that the supply of labor to a given <u>sector</u> is quite different from the supply of labor in the <u>aggregate</u>.

Even if total labor supply is wage-inelastic, changes in the manufacturing wage appear able to induce large reallocations of labor between sectors.[6] This finding will be seen to have much bearing on the explanation of productivity variation.

The parameter estimates given in Table 6 imply a fitted covariance matrix $\Omega(\hat{\Theta})$ for the variables v. The fitted matrix, given in Table 7, may be compared with the actual sample covariances reported in Table 4. The matchups are reasonably good, though there are misses. The contemporaneous covariance matrix (the top third of each table) contains the covariances which are largest in magnitude and is thus especially important as a check on the estimates. Here the model has caught most of the features of the data. The variances of q_t, p_t, w_t, n_t, and k_t are well-predicted. The large covariance of production and labor input is captured. The fitted covariances of the other variables with capital inputs are too high, however.

As has been mentioned, the model reported here was representative of a small number of similar models with which we experimented. Although the details of these models differed, they provided very similar estimates of the variances of the unobservable shocks. We turn now to these estimates.

Table 7

FITTED COVARIANCES

	q_t	p_t	w_t	n_t	k_t
q_t	.3997				
p_t	.0146	.0651			
w_t	.0205	-.0100	.0305		
n_t	.3688	.0379	.0167	.3756	
k_t	.0661	.0150	.0005	.0589	.0625
q_{t-1}	.0030				
p_{t-1}	-.0137	.0015			
w_{t-1}	.0105	-.0018	.0072		
n_{t-1}	.0026	.0279	.0147	.0022	
k_{t-1}	-.0063	.0008	.0035	-.0054	.0403
q_{t-2}	-.0168				
p_{t-2}	-.0023	-.0117			
w_{t-2}	.0018	.0084	-.0048		
n_{t-2}	-.0145	.0016	.0018	-.0124	
k_{t-2}	-.0016	-.0051	.0050	-.0009	.0124

Note: Data are multiplied by 100 for notational compactness.

6. Decomposing Productivity Variation

In our model permanent variations in productivity can be caused by four different types of unobservable shocks:

1. Shocks to product demand (ε^d)
2. Shocks to the production function (ε^q)
3. Shocks to labor supply (ε^n)
4. Shocks to capital costs (ε^k)

The effects of each broad type of permanent shock on productivity were analyzed in Section 2.

In addition, temporary productivity changes can be induced by transient or "cyclical" shocks (ε^y), which cause utilization rates U_t to depart from normal levels.

The estimated variances of these shocks are reported in lines 1-5 of Table 6. The variance of labor supply shocks is by far the largest, being an order of magnitude greater than the variances of the shocks to product demand and to capital costs. The latter are, in turn, about ten times the size of the variances of production function and cyclical disturbances.

The raw variances alone do not tell us the relative importance of the sources of productivity variation, however, because each type of shock affects productivity with a different weight. To see this, use lines (1) and (4) from Table 5 to write the growth rate of labor productivity, q - n, as

$$(11) \qquad q - n = q^* - n^* + (1 - \beta_n)y$$

Using the model solution in the appendix to find an expression for $q^* - n^*$, we get

$$(12) \qquad q - n = 1/\Delta \; [(1 - \alpha_n)\, \varepsilon^d + (\eta^s - \eta^d)\, \varepsilon^q + (\alpha_n - 1)\, \varepsilon^n + \alpha_k\, (\eta^d - \eta^s)\, \varepsilon^k] + (1 - \beta_n) y$$

$$\text{where} \quad \Delta = \alpha_k + \eta^s - \alpha_n \eta^d$$

Inserting estimated values for η^d, η^s, β_n and prior values for α_n, α_k, then squaring and taking expectations, we find that[7]

$$(13) \qquad \text{var}(q-n) = .00155\, \sigma_d^2 + .94804\, \sigma_q^2 + .00155\, \sigma_n^2 + .08532\, \sigma_k^2 + .01988\, \sigma_y^2$$

With the weighting in (13) we can calculate the productivity variance decomposition given in the first part of Table 8. The results are striking. Almost 90% of the variance in manufacturing labor productivity in the 1947-80 period can be attributed to shocks to the production function and to capital costs. Changes in product demand and labor supply, together with transitory influences, are relatively insignificant factors.

Can this result be explained? The negligible influence of the cycle is easy to rationalize; it has already been suggested (Section 4) that the nature of the data is such as to minimize cyclical effects. The explanations of the small impacts of product demand and labor supply shifts can be seen to center on the large estimated sensitivity of sectoral labor supply to real wage changes: 1) Shocks to demand can have permanent effects on productivity only if, by changing the scale of production, they result in a significant change in the capital-labor ratio. When both capital and labor are elastically supplied to the sector in the long run, the optimal

Table 8

SOURCES OF PRODUCTIVITY VARIATION

1. Estimates from entire sample (1947-80)

Source of Shock	Share of Variation
Product demand	1.54%
Production function	53.07%
Labor supply	6.55%
Capital costs	36.54%
Cyclical or transitory	2.30%

2. Estimates from 1947-69 subsample

Source of Shock	Share of Variation
Product demand	1.78%
Production function	55.76%
Labor supply	5.54%
Capital costs	35.48%
Cyclical or transitory	1.44%

3. Estimates from 1970-80 subsample

Source of Shock	Share of Variation
Product demand	1.18%
Production function	51.58%
Labor supply	7.40%
Capital costs	36.47%
Cyclical or transitory	3.37%

capital-labor ratio is insensitive to the scale of production; thus the effect of demand on productivity in the long run is small. 2) Shocks to labor supply affect productivity through a similar channel. A disturbance to the intercept of the labor supply curve, by changing the equilibrium real wage, modifies the optimal capital-labor ratio and thus the chosen level of productivity. But again, if the elasticity of labor supply is large this effect on productivity is weak. A high elasticity means that only small wage movements are needed to offset labor supply shocks, so that the capital-labor ratio and the level of productivity remain insulated.

On the other hand, an elastic sectoral labor supply does not prevent production function and capital cost disturbances from affecting productivity. Given the stability of the manufacturing real wage at different levels of employment, changes in capital costs are able to influence desired capital-labor ratios significantly in the long run; the productivity response may be large. Shifts in the production function do not change the capital-labor ratio in an important way, but they affect labor productivity directly by changing overall factor productivity. This channel is insensitive to the labor supply response. Thus, given the estimate of η^s, the dominance of these last two factors in the explanation of productivity changes is to be expected.

The importance of capital cost changes in the variance decomposition is an informative result. It confirms the notion that factors such as energy prices, taxes on investment goods, real interest rates, and the supply prices of new capital are crucial for productivity in the long run. Note that this is not the same as saying that productivity depends on the level of capital investment *per se*. For example, an expansion of the capital stock caused by a permanent increase in the demand for manufacturing output would be associated primarily with an increase in sectoral employment, not an increase in productivity. Similarly, an unanticipated change in capital costs could affect productivity through capacity utilization, hiring, and pricing decisions well before the capital stock could respond.

The large (one might say, preponderant) role of production function shocks in productivity determination provides somewhat less information. Like Denison's famous "residual", this is a catch-all category that includes not only technological and managerial factors but also any errors of measurement of inputs (e.g., because of changes in input quality) or of outputs (as when increased "production" of worker safety is substituted for directly measured output). Aggregate analysis of the sort done here cannot hope to sort out the many miscellaneous factors that enter this category; it can only suggest that the returns to more detailed study are potentially great.[8]

Productivity trends have changed quite a bit in the last decade. To find out if this would show up in the analysis of productivity variation, we held the incidental parameters (6-19) fixed and re-estimated the five shock variance for the sub-periods 1947-69 and 1970-80. The decompositions are given in the bottom two-thirds of Table 8.

The results for the two periods appear similar; disturbances to the production function and to capital costs are still the dominant causes. However, this way of presenting the data tends to conceal some differences between the subsamples: In Table 9 the relative sizes of the estimated shock variances from the two periods are reported. The 1970-80 period was clearly the more turbulent, as only the variance of shocks to product demand was smaller than in 1947-69. The heavily-weighted production

Table 9

RELATIVE SIZE OF ESTIMATED VARIANCES OF SHOCKS FOR TWO SUBSAMPLES

Variance	Definition	Estimated Size for 1970-80, Relative to 1947-69
σ_d^2	Variance of shocks to product demand	.849
σ_q^2	Variance of shocks to production function	1.186
σ_n^2	Variance of shocks to labor supply	1.712
σ_k^2	Variance of shocks to capital costs	1.318
σ_y^2	Variance of cyclical shocks	3.000

function disturbances were 18.6% more variable after 1970. The 71.2% increase in the variance of labor supply shocks and the 31.8% expansion in the capital costs variance are consistent with our perceptions of the last decade. Fianlly, cyclical effects were fully three times as large in the 1970s.

The comparative analysis of the two periods demonstrate the usefulness of the econometric approach of this paper. It is possible, we have shown, to agree that the last ten years have seen large disturbances in labor markets (e.g., due to demographic factors) and in the business cycle; and yet simultaneously to argue that these disturbances have had relatively unimportant effects on manufacturing productivity. Capital utilization costs and the factors subsumed by the term "production function shocks" are the principal explanations of the recent productivity experience.

7. Conclusion

Traditional growth accounting methods, which study the co-movements of jointly endogenous variables, provide little information about the direction, magnitude, or channels of causal relations. The econometric method used in this paper shows how productivity changes can be linked with exogenous causes, even though those causes are not directly observable.

There are obvious ways in which the analysis of productivity through this method could be extended, e.g., different or more refined data sets and model specifications. There is also scope in this approach for gaining more information about the "black box" of changes in the production function.

A point that should be made, however, is that the choice of productivity as the variable upon which to focus the discussion of our results was an arbitrary one. Any endogenous variable in the model could have been analyzed in the same detail without further estimation. For example, the reported results are all that is needed to do a rather detailed study of capital formation in the manufacturing sector. This analysis would not only assess the importance of different sources of capital formation but would provide time patterns of response of the capital stock to each kind of exogenous change. This provision of information in several different areas is another advantage of the explicitly structural modelling approach employed in this paper.

APPENDIX

SOLUTION OF THE MODEL IN TABLE 1

The solution for the desired growth rates may be written as the reduced form

(1) $\tilde{v}^{*\prime} = A\varepsilon^{*\prime}$

where $\tilde{v}^* = (q^*,\ p^*,\ w^*,\ k^*)$

$\tilde{v}^* = (\varepsilon^d,\ \varepsilon^q,\ \varepsilon^n,\ \varepsilon^k)$.

The matrix of coefficients A is given by

$$A = \frac{1}{\Delta}\ x \begin{bmatrix} (\alpha_k+\eta^s) & -\ \eta^d(\eta^s+1) & -\ \alpha_n\eta^d & \alpha_k\eta^d(\eta^s+1) \\ \alpha_n & -\ (\eta^s+1) & -\ \alpha_n & \alpha_k(\eta^s+1) \\ 1 & -\ (\eta^d+1) & -\ 1 & \alpha_k(\eta^d+1) \\ 1+\eta^s & -\ \alpha_n(1+\eta^d) - \eta^d(\eta^s+1) & -\ \alpha_n(1+\eta^d) & \begin{array}{l} \alpha_k\eta^d(\eta^s+1) \\ +\alpha_k\alpha_n\eta^d \\ -\alpha_n\eta^s + \alpha_n^2\eta^d \end{array} \end{bmatrix}$$

where $\Delta = \alpha_k + \eta^s - \alpha_n\eta^d$

Notes

1. Additions to inventories will be treated as part of purchases, for simplicity.

2. This specification is convenient in that it allows the difficult-to-measure full cost of capital to be treated as an unobservable in the econometric work. The assumption that X_t^k is exogenous is empirically reasonable, since the feedback of variations in U.S. manufacturing demand for capital to long run capital utilization costs (such as the cost of energy) is certainly small. (In our estimates below, we find that even labor costs may nearly be treated as exogenous to the manufacturing sector.) The exogeneity of X_t^k is not tantamount to perfect elasticity of capital supply in the short run, since later we will assume adjustment costs are associated with changes in input stocks.

3. See Varian (1978), p. 15.

4. The desired growth rates v* were derived, recall, under an assumption of no adjustment costs. Gradual adjustment of actual towards desired rates is a way of reintroducing these costs in the empirical specification.

5. Alternative AR and MA processes were tried; the results were not affected.

6. That is, $\hat{\eta}^s$ measures the response of manufacturing labor supply to changes in the manufacturing wage, given the national wage level. The national wage is exogenous to the manufacturing sector and is thus subsumed in X_t^n.

7. Recall that the expression σ_y^2 is the variance not of the transitory process y but of its innovation ε^y. (13) uses the relation

$$\text{var}(y) = \sigma_y^2/(.8406)$$

which is derived by inserting the estimates of ρ_1 and ρ_2 in the expression for the variance of an AR(2) process.

8. There is no shortage of such attempts. Denison himself has analyzed the "residual" in some detail in his 1978 articles.

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