DECOMPOSING TECHNICAL CHANGE

By

Michael Gort
State University of New York
at Buffalo

Byong H. Bahk
Dong-A- University
Korea

Richard A. Wall
Canisius College

CES 91-4 May 1991

Bureau of the Census, Washington, DC   20233-6300, (301-763-2065)
or INTERNET address snguyen@info.census.gov.

Abstract

A production function is specified with human capital as a separate argument and with embodied technical change proxied by a variable that measures the average vintage of the stock of capital. The coefficients of this production function are estimated with cross section data for roughly 2,150 new manufacturing plants in 41 industries, and for subsets of this sample.

The question of interactions between new investment and initial endowments of capital is then examined with data for roughly 1,400 old plants in 15 industries.

Keywords: Embodied Technical Change, Capital Productivity

The project was carried out with assistance from the ASA/NSF/Census fellowship program. The authors are, of course, solely responsible for the conclusions and methods of analysis used.

Within the conventional neoclassical framework, a distinction is sometimes made between product-augmenting and factor-augmenting technical change. A parallel distinction is commonly made between embodied and disembodied technical change with the former associated with factor, and the latter with product, augmentation. Disembodied change is commonly assumed to arise from increases in the stock of knowledge, independently of the characteristics of the inputs used, while embodied change relates to increases in the efficiency of inputs, that is, labor skills or the productivity of physical capital.

Unfortunately, this distinction is ambiguous. Changes in the efficiency of the inputs used are usually accompanied--indeed made possible--by increases in knowledge. And conversely, increases in the stock of knowledge often favor some inputs more than others, including the capital goods of one vintage relative to those of another. This becomes obvious when one considers that purchases of capital goods in successive years are unlikely to be functionally identical in their composition.

Notwithstanding the ambiguity, the concept of embodiment has intuitive appeal and this partly explains the focus on decomposing the sources of technical change that followed Solow's (1957) seminal paper. But by the late 1960's, a reader of the literature might have concluded that such decomposition was impossible. For with merely time series data on inputs and output, product, augmenting and factor-augmenting technical change are empirically indistinguishable.

In an important paper, Hall (1968) showed that with data on used equipment prices and the interest rate, embodied technical change and deterioration function can, in principle, be calculated. However, the paucity of data on the prices of used capital goods has allowed little progress in this direction. The new Longitudinal Research Database created by the U.S. Bureau of the Census now permits still another approach to the estimation of "embodied" technical change associated with capital, both physical and human. In addition, it casts light on a perplexing problem that has plagued econometric estimates of production relations based on <u>changes</u> in inputs and output as distinct from <u>levels</u> of both.

This new body of information consists of time series and cross section data for individual manufacturing plants for the period 1972 to 1986. The time series permit us to derive indexes of the vintage of capital for each plant. This, in turn, allows us to estimate the effects of vintage of capital on productivity from strictly cross-section data. And since these effects are estimated at a common point in time, temporal shifts in productivity divorced from vintage are excluded by definition.

Moreover, we are also able to distinguish between "new" plants--that is, plants without endowments of capital accumulated in earlier periods--from "old" plants. The analysis of data for old plants allows the test of a hypothesis, and yields an explanation, of why estimates based on changes in inputs and output generally lead to very different coefficients from those based on levels of the variables. The latter is an issue with important policy implications given that most investment in developed economies takes the form of expansion -- that is, changes in inputs -- for existing (old) plants.

The remainder of the paper is divided into six sections. In Section I we present our principal model and the definitions of variables in our production function. Section II reports the estimates for technical change in the context of <u>levels</u> of inputs and output for <u>new</u> plants. Section III discusses the implications of measuring production relations for <u>changes</u> in inputs and output as distinct from <u>levels</u> while Section IV presents estimates for old plants based on changes in the relevant variables. Section V compares the results for new and old plants while Section IV is a brief summary of principal conclusions. There is also a short appendix on data construction.

I. MODEL FOR MEASURING TECHNICAL ADVANCE AND DEFINITION OF VARIABLES.

We start with a general model

$$O_J = A_J e^{aJ} H_J(\bar{I}_J, L_J, Q_J) \tag{1}$$

where O_J is output, A_J is a shift parameter that is assumed to affect the productivity of all vintages of capital and all labor skills symmetrically, L_J is labor, Q_J is human capital, and $\mathbf{I}_J$ is a vector of investment streams.

$$\mathbf{I}_J = (I_J, \; ..., I_{J-(+1})\qquad(2)$$

where J is the vintage year in which investment is measured, and (is the age of the plant.

As is commonly hypothesized, we expect each successive vintage of investment to be more productive than the last so that,

$$\frac{\partial H_\tau}{\partial I_\tau} > \frac{\partial H_\tau}{\partial I_{\tau-1}}.\qquad(3)$$

Let us assume we can substitute a capital stock variable for the vector of investments and take due account of the effect of vintage by measuring the average vintage of the stock. Accordingly, we have

$$O = AE^{aJ}F(K_v e^{kv}, L, Q)\qquad(4)$$

where K is the sum of investments of various vintages, v is the weighted average vintage of the stock with weights based on the investment of each vintage relative to K, and k measures productivity enhancement from "embodied" effects of vintage (the subscripts of J are omitted).

The resulting model differs in several respects from production functions that are commonly estimated. First, human capital (labor skills) enters as a separate argument in the production function rather than as an adjustment to the measure of labor input. Second, capital is composed of gross investment streams, rather than net investment, so that the effect of vintage (that is, obsolescence plus decay) is estimated within the framework of the model. In this respect, our approach accords with that of Prucha and Madiri (1990), though we do not follow them in their assumption that the depreciation rate is endogenous. It contrasts with the conventional method of inferring obsolescence and deterioration from assumed economic lives and decay functions.

Our conceptual framework makes no distinction between the accumulation of knowledge and changes in the physical attributes of capital associated with vintage as long as new knowledge is uniquely related to vintage. Similarly, if new knowledge is uniquely related to labor skills, no distinction is made between the two. Changes in the shift parameter, A_J, disappear within a cross-section framework and only interplant variations in "disembodied" technical change remain.

Differences across plants in blueprint technology, and in the knowledge associated with it, are almost certainly uniquely related to either labor skills or the vintage of physical capital. What, then, is there left of disembodiment in the context of a cross-section model? It appears that only the effects of organizational capital, largely in the form of firm-specific information, remain unaccounted. Such organizational capital may take the form of matching of tasks with the attributes of individual employees, the sorting of employees by competence, and other aspects of firm-specific learning-by-doing. This form of disembodiment is excluded from our model.

We next turn to a more detailed discussion of the variables in equation (4).

A. Physical Capital and Vintage

The stock of capital in equation (4) is the sum of gross investments from the year following the birth of the plant to the year in which output is measured. Obsolescence is then measured directly via the production function through estimates of the effect of vintage on output.

The effects of vintage arise from obsolescence + (physical decay - maintenance outlays). If, however, as is plausible, maintenance outlays roughly offset the effects of physical decay at least on current production (if not also on earnings), the principal source of difference in the relative efficiency of capital of different vintages is obsolescence. The implied depreciation rate then, correctly measured, becomes roughly the dual of capital augmenting technical change.

The foregoing indicates that the assumptions necessary to construct a net capital stock require implicitly a measure of embodied technical change of capital. And if physical decay roughly equals maintenance outlays, then obsolescence is all that needs to be measured to transform gross into net stocks.

Vintage was measured as the weighted average of the years of the investment stream for each plant, with weights based on the ratio of the annual investment for each plant to its total investment over the relevant period. By definition, a higher average indicated more recent vintage. Thus vintage measured (inversely) the average age of physical assets.

Since the productivity of an asset has a lower bound of zero, in principle, only non-retired assets should be included in the computation of average vintage. Otherwise, a systematic relation between the stock of retired assets and average vintage might lead, in the context of a production function, to distortions in the coefficients of both physical capital and vintage. However, since the period over which average vintage was computed was limited to 1973-86, retirement of assets from the relevant investment streams (as our tests showed) were not large enough to distort the estimates significantly and were, therefore, ignored.

In fact, plant data for retirements were available and experiments were carried out with the use of retirement data as a separate explanatory variable. The results were largely negative in the sense that retirements in the 1973-86 period did not prove to have significant explanatory power. This is consistent with an assumption of gradual decline in the productivity of assets as they obsolesce. Under such conditions, the flow of productive services from old assets will approach zero as they approach retirement.

Consequently, the final step of retiring assets should change output very little, if at all.

Excluded from the model is circulating capital (that is, inventories). This is justified since inventory accumulation is, at least partly, unintended and is also a function of expected future rather than merely current output.

B. Labor and Human Capital

Our labor variable was intended to approximate pure labor independently of human capital (labor quality) and was thus measured by the number of employees for each plant. Our index for the average amount of human capital associated with the labor input was simply the average wage rate for each plant.[1] In effect, we assumed that all plants have equal access to the labor market and that differences in average wages must reflect differences in human capital. This, of course, deviates from common methodology that assumes variations in wage rates measure differences in price for identical classes of labor. If our assumption of equal access to labor markets is correct, it renders unnecessary inferences about

[1] To facilitate the interpretation of the coefficients of change in human capital, as well as to correct for possible biases arising from the fact that in some of our cross-sections the observations do not relate to identical points in time, average wage rates were deflated. The deflator was the Consumers' Price Index and was intended simply to correct for the average rate of inflation in the economy.

labor quality from information on education, occupation, or demographic attributes of employees.

Our chosen measure is implicitly based on a definition of human capital as any attribute of labor that increases its productivity. Across plants at a point in time, we assume that average wage rates reflect primarily differences in the composition of the work force with respect to what Becker (1964) has called general (as distinct from firm specific) human capital--that is, human capital the returns to which are probably captured by the employee.

Differences in average wage rates across plants in the same industry were far too large to permit a conclusion that they reflected regional variations in wages. More specifically, for most industries, the highest average wage for any plant was roughly three times the lowest, and the standard deviations were typically between 20 and 30 percent of the mean wage. This represents a far greater variation than can plausibly be attributed to such factors as unionization, historical peculiarities, or regional differences in wages.

Even more decisive, if historical accident or unionization were important explanatory variables for the dispersion in average wages across plants, one would expect the variation to be larger for old than for new plants. All new plants cn choose their location and, therefore, at the outset face common labor markets. In fact, the dispersion in average wages was larger for new than for old plants. This reflects the role of competing technologies with substantial trade-offs between human capital and other inputs rather than unionization or regional variations in wages.

As a final check, we divided all plants into the nine Census geographic regions to assess to what extent variations in average wages were attributable to regional influences on wage rates. We found that, generally, one could not predict the regional pattern of high and low wages for one industry from the observed pattern for another industry.

C. Output

The dependent variable, output, was proxied alternatively by deflated shipments and by deflated value added. For reasons indicated in the appendix, both shipments and value added have deficiencies as measures of output. The choice between them depends partly on the set of industries examined. For this reason, results are generally presented with both variables as alternatives.

II. ESTIMATES OF EMBODIED TECHNICAL CHANGE BASED ON DATA FOR NEW PLANTS

From the standpoint of our analysis, the central distinction between "new" and "old" plants is not their chronological age but whether, at the starting date for analysis, there are initial endowments of physical capital that originate from earlier investments. If there are none, or if they are minor, we classify the plants as "new". The relevance of this distinction rests in our hypothesis (developed more fully later) about interactions between new investment and the initial capital stock. These interactions lead to non-separability of the relation between new inputs and changes in output and, hence, to unstable and misleading coefficients in the context of a production function.

Interactions across successive investment streams also occur for new plants with no initial endowments of capital. But, as explained later, for new, in contrast to old, plants interaction effects are far more likely to be proportional to cumulated new investment. First, across new plants, the stock of capital is far more homogeneous in its age composition. Second, for new plants investment streams of contiguous years are frequently elements of an integrated investment plan.

New plants were defined as plants born in 1973 or later while old plants were those in existence in 1972 (the initial year for the available data set). New plants were in fact considerably younger than old plants and, further, the bulk of their capital outlays were made within several years of their birth.

The analysis was carried out with data for plants in a set of 41 manufacturing industries, and a subset of 32 industries, over the 1973-86 period. The industries were selected mainly on the basis of the number of new plants encompassed by each industry but, in general, the 41 industries appear to be broadly representative of the manufacturing spectrum. All told, the analysis is based on a sample of close to 2200 plants. Details of the selection of plants and industries, and a list of industries, are included in the appendix.

<u>A. The Econometric Model</u>

The production function (equation 5) was estimated in augmented Cobb-Douglas form for capital and labor inputs. The customary Cobb-Douglas specification was modified by the inclusion of an index of human capital as a separate argument in the production function. Further, we included an average vintage variable--the latter not in log form but rather in average number of years. Preliminary experiments with CES and Translog specifications yielded clearly inferior results.

$$\log O_{jt} = \$_{ot} + \$_{lt} \log L_{jt} + \$_{2t} \log Q_{jt} + \$_{3t} \log K_{jt} + \$_{4t} V_{jt} + u_{jt} \qquad (5)$$

where the variables O, L. Q, K and V are defined as before and each variable is measured for plant j in time t.

Data were pooled for plants in all the industries in the sample. To assess the difference between estimated coefficients for each industry and those for the aggregate sample, a dummy variable model was developed. It estimates <u>simultaneously</u> the coefficients for all plants in all industries in addition to the <u>difference</u> in each industry coefficient from that for the aggregate. The equation is:

$$\log O_{jt} = \$_{ot} + E\ \$_{oit} D_i$$

$$
\begin{aligned}
&+ \quad \$_{1t} \log L_{ijt} && + E\ \$_{lit}\ D_i \log L_{ijt} \\
&+ \quad \$_{2t} \log Q_{ijt} && + E\ \$_{2it}\ D_i \log Q_{ijt} \\
&+ \quad \$_{3t} \log K_{ijt} && + E\ \$_{3it}\ D_i \log K_{ijt} \\
&+ \quad \$_{4t}\ V_{ijt} && + E\ \$_{4it}\ D_i\ V_{ijt} \\
&+ \quad u_{ijt}
\end{aligned}
$$

where O, L, Q, K, and V are defined as above for plant j in period t, D_i takes the value of one for industry i, zero otherwise, and each E is summed over the industry index i=1...41. The values for $\$._{t}$ are the aggregate coefficients, while those for $\$._{it}$ measure the differences in industry coefficients from those for the aggregate. Thus $\$._{t} + \$._{it}$ are the coefficients for each industry.

The model was constructed by stacking all observations twice to avoid the "dummy variable trap" (thus doubling the number of observations for each cross-section). The first stack specifies the basic model in equation (6), then includes zeros for all industry dummies for each variable. The second stack again specifies the basic model in equation (6), but this time the added dummy variables take the value of one for a particular industry for each variable (5 dummies for each industry), and zero otherwise.

The estimates for the coefficients for the aggregate are unchanged. The stacking procedure, however, artificially increases the sample size by more than the degrees of freedom lost in using the large number of dummies. Test for significance are thus somewhat biased in the direction of rejecting the null hypothesis of no differential industry effect.

B. Results

Table 1 presents the results for equation (5) for two samples of industries, 41 and 32, and using two alternative proxies for output, namely, shipments and value added. In addition, for each alternative the results are shown for all plants born between 1973 and 1986 and for those born at least three years before the terminal peak for each plant (that is, the point for which the cross-section data are analyzed).

Limiting the data to plants born at least three years prior to the terminal peak had the purpose of allowing sufficient time for capital goods to be fully phased in and, hence, for the estimates to correspond to the production frontier. In fact, this

Table 1

PRODUCTION RELATIONS FOR NEW PLANTS, POOLED DATA FOR 41 AND 32 INDUSTRIES

(Numbers in parentheses below the coefficients are t-values.)

Dependent Variable	Inter-cept	L	Q	K	V	Adjusted R^2	Sample Size
			41 Industries, All Observations				
Shipments	1.82	.67	.59	.31	.02	.81	2,168
	(11.64)	(45.81)	(12.28)	(21.17)	(3.35)		
Value Added	.65	.66	.69	.29	.04	.77	2,173
	(3.83)	(41.55)	(13.07)	(18.12)	(5.66)		
			41 Industries Limited To Plants Born at Least 3 Years Prior to Terminal Peak				
Shipments	1.71	.61	.53	.36	.04	.77	1,212
	(8.16)	(28.45)	(7.80)	(15.32)	(4.40)		
Value Added	.47	.63	.66	.32	.06	.73	1,212
	(2.08)	(26.95)	(8.90)	(13.56)	(6.21)		
			32 Industries, All Observations				
Shipments	1.85	.67	.54	.33	.02	.82	1,919
	(11.19)	(44.16)	(10.58)	(20.81)	(3.38)		
Value Added	.75	.64	.63	.31	.04	.78	1,922
	(4.20)	(39.09)	(11.45)	(18.16)	(5.61)		
			32 Industries Limited To Plants Born at Lease 3 Years Prior to Terminal Peak				
Shipments	1.67	.62	.48	.38	.04	.78	1,068
	(7.48)	(27.58)	(6.34)	(14.89)	(3.89)		
Value Added	.46	.62	.63	.34	.06	.74	1,068
	(1.90)	(25.25)	(8.11)	(12.40)	(5.87)		

Source: U.S. Bureau of the Census, LRD database.

Output and inputs, with all variables except vintage specified in logs, are measured for the peak year (out of 1984, 85, or 86) of the plant's operations except that physical capital is lagged half a year. L is measured by number of employees, Q by the average wage rate, K by cumulated capital expenditures and initial purchases of assets plus the capitalized value of the change in rentals, and V by the weighted average age of investments (with higher values for more recent investments). The dependent variable, log of output, is measured by shipments and, alternatively, by value added. The detailed measurement procedures are discussed in the text and appendix, with the list of industries shown in Table A.

restriction, based at least on R_2 values, did not seem to improve the estimates--a result that may stem from the change in sample composition and reduction in sample size.

In general, the coefficients for labor, human capital, and physical capital are highly stable across the eight set of estimates, the median values for the three coefficients being .64, .61, and .33, respectively. There is considerably more volatility from sample to sample for the coefficients for vintage, with the median value being .04. The R^2 and t values, considering that cross-section data for a highly diverse group of industries were used, are all very high.

The principal contributions of the econometric model is that it enables the measurement of the effects on output of embodied technical change, and of human capital separate from "pure labor." To focus first on the latter, we observe from Table 1 that, particularly for estimates with value added as the dependent variable, the elasticity of output with respect to human capital is roughly the same as that for pure labor.

Given our definitions, a one percent change in human capital (measured by the average wage) must have the same effect on total costs as a one percent change in the labor input (measured by number of employees). Accordingly, the same coefficients for the two variables mean that the marginal products per dollar of expenditures are the same for the two inputs. The consistency of this result with an optimal input allocation rule is an outcome one might have expected from data drawn from an industry with a homogeneous output. It is surprising given the variety of industries and technologies from which the plants were drawn, as well as the enormous range of plant sizes encompassed by the samples.

The most frequent estimate for vintage yielded a coefficient that indicated a four percent change in output for each one-year change in the average vintage of the stock of capital. This is indeed a high value given that gross returns to capital have a weight of roughly one-third in total inputs for manufacturing industries (as measured by capital's share of gross compensation to capital plus labor, and using Statistics of Income data for 1972-86). Thus a 4 percent change in output attributed solely to embodied technical change for physical capital implies about a twelve percent change in the efficiency of capital goods from a one-year change in average vintage (.04/.33).

While there was some instability in the estimated coefficients for vintage, such estimates can only be viewed as rough approximations of average rates of change attributable to the age of capital goods. Not only is each year's investment composed of large numbers of specific capital goods, but the functional composition of capital goods (for example, structures versus equipment or office equipment versus transportation equipment) undoubtedly changes across vintages. Thus, the derived measures are meaningful only as approximations or scalar magnitudes rather than as point estimates.

Using equation (6) to estimate industry dummies, we find that for most industries the dummy variables were not significant--that is, industry estimates for the coefficients did not deviate significantly from the estimates for the combined sample. The results are summarized in Table 2 which shows that for only a small fraction of the 41 industries did any of the industry estimates deviate significantly from those for all industries combined.

Table 2

DIFFERENCES BETWEEN INDUSTRY COEFFICIENTS AND THOSE FOR POOLED DATA FOR 41 INDUSTRIES IN TABLE 1

Dependent Variable	Dummy	Number of Significant Coefficients (+)	(-)	Number of Non-Significant Coefficients
Value of Shipments	D	1, 1	2, 0	37
	D*L	3, 2	1, 1	34
	D*Q	5, 1	3, 2	30
	D*K	0, 1	4, 6	30
	D*V	0, 2	1, 0	38
Value Added	D	2, 0	1, 1	37
	D*L	4, 4	1, 0	32
	D*Q	2, 0	4, 3	32
	D*K	1, 0	6, 3	31
	D*V	0, 2	0, 2	37

D: industry dummy, L: labor, Q: human capital, K: capital, V: vintage. For the number of significant coefficients, two numbers are reported: the first number reports strong significance ($p<0.05$) and the second "marginal" significance ($0.05<p<0.10$).

III. MODELING PRODUCTION RELATIONS FOR CHANGES IN INPUTS AND OUTPUT

The average proportion of capital expenditures in U.S. manufacturing that is spent on existing plants, as distinct from those under construction, has been estimated by Gort and Boddy (1967) to exceed 90 percent of the total. But even using a much looser definition that classifies plants in the several years following their initial operation as new, the proportion accounted for by older plants would be a large fraction of the total.

At first glance, this fact seems puzzling. The addition of new capital goods to a production process already in place and incorporating old assets must be restricted in the kinds and combinations of inputs that can efficiently be added. Why then do firms choose to give up the flexibility and consequent economies associated with new plants of best practice technology? Why do they, instead, expand within the limitations of melding older and newer capital goods?

There are three plausible explanations for investment in old establishments. First, their expansion may entail a shorter gestation period than creation of new plants. Second, scale economies may preclude the creation of new plants for small increases in output. And third, total input requirements for a given increase in output may be smaller for old plants because of interactions between old and new inputs. It is this third explanation that is the focus of our attention.

There are two principal ways in which such interactions may occur. First, new employees may learn from older ones thereby reducing adjustment costs. Second, new physical assets may interact with old ones by modifying them, or at least changing the way in which old assets are used. In this way, new capacity could be created with lower inputs of physical capital than required when starting from a zero base.

It is our hypothesis that <u>increments</u> in output entail different production function coefficients from those implicity in <u>levels</u> of output and inputs and that this, in turn, is a consequence of interactions. Were it otherwise -- that is, in the absence of interactions -- new inputs of capital (investment) on old plants could be viewed as separable <u>levels</u> of capital just as increases in output could similarly be viewed as the <u>level</u> of new output.

Gort and Boddy (1967) modeled interaction effects through a simple multiplicative term -- a procedure that made sense for the electric power industry they studied since the interaction took largely the form of addition of generating equipment to old structures, or of modifications of boilers for existing steam turbogenerators. The assumption of a symmetrical effect of new investment across all old capital goods as implied by a multiplicative term is, however, much too simple to capture the technological interactions observable in most industries. Indeed, interactions are difficult to model since they are likely to vary across plants within an industry as well as across industries. But this does not mean that their effects can be ignored. Fortunately, there is a solution to the problem.

Interactions occur across all vintages of investment. The fact that one year's investment may be composed of structures while the next year's is composed of equipment housed by the structures, means that growth in output cannot be expected to respond in a consistent way to a single year's investment outlays. Outlays over several years are likelier to reflect a balanced investment plan than those for a single year and, hence, (holding technology constant) are likelier to produce a proportional relation between growth in output and cumulated investment. But a balanced investment program still does not dispose of interactions that take the form of modifications of old assets made possible by new technology. Nor does it take account of differences in returns to new investment from interactions arising because of large differences across plants, at any point in time, in the size of the initial stock of capital.

It is plausible, however, that interaction effects associated with the stock of old assets existing at the outset decline as a function of time, relative to the separable output effects of new investment. Old plants vary not only in the magnitude of their initial capital endowments but also in the age of their old capital. Consequently when new investment is still small relative to old investment, interactions between new and old capital will produce unsystematic and, hence, unpredictable effects in the context of cross-section analysis. The problem, therefore, reduces itself to one of finding a subsequent point in time at which interaction effects across plants become sufficiently systematic that they can be measured.

Consider equation (7) for old plants

$$O_J = H_J\ (\mathbf{I}_J,\ K_0,\ L_J,\ Q_J) \tag{7}$$

where J is the vintage year (with $J = 0$ the base year), O_J is defined as output, $\mathbf{I}_J$ the vector of current vintage year and previous investments such that $\mathbf{I}_J = (I_J, I_{J-1}, \ldots, I_0)$ K_0 the initial capital stock, L_J is labor, and Q_J is labor quality. The hypotheses concerning embodied technical change can be summarized as follows:

$$\frac{\partial H_\tau}{\partial I_\tau} > \frac{\partial H_\tau}{\partial I_{\tau-1}}. \qquad (8)\ (i)$$

$$\frac{\partial^2 O_\tau}{\partial I_\tau \partial I_{\tau-i}} > \frac{\partial^2 O_\tau}{\partial I_\tau \partial I_{\tau-j}} > 0 \quad \text{for } i < j \qquad (ii)$$

$$\frac{\partial O_\tau}{\partial K_0} > \frac{\partial O_{\tau-1}}{\partial K_0} \qquad (iii)$$

Equation (8)(i) shows, as before, the greater productivity of more recent vintages of investment. The effect of interactions is shown in equation (8)(ii) by the positive (if any) contribution of more recent vintage investment, denoted by J, to the marginal productivity of past investments denoted by J-i and J-j. Interaction effects will be larger between investments of shorter time lapse between vintages (i<j) because old assets become progressively less adaptable to new capital. Finally, with obsolescence, the productivity of the initial capital stock, equation (8)(iii), declines over time. While not reflected in the above equations, the <u>relative</u> effect on output of interactions with K_0 declines over time for still another reason. As the sum of new investments grows over time, their separable effects on output, and the interactions across the new investments, grow in importance relative to the effects of K_0.

If one assumes that both vintage and interaction effects are of no consequence (out <u>null</u> hypothesis), the production function for vintage year J can be expressed as

$$O_J = h_J\ (K_J,\ L_J,\ Q_J) \tag{9}$$

where K_J is the capital stock aggregated from the investment vector and the initial stock. Now define $)O_J = O_J - O_0$, where $O_0 = h_0(K_0, L_0, Q_0)$ under the null hypothesis stated above (that is, with no embodiment). the <u>increment</u> to output relative to the base year level should then be a separable production function [2] expressible as

$$)O_J = h_J\ ()K_J,\ )L_J,\ Q_J) \tag{10}$$

---

[2] The mathematical conditions necessary for exact separability of output and input levels into functions based on increments is, to our knowledge, unsolved.

where $)K_J = H_J - K_0$ and $)L_J = L_J - L_0$ measure the increments to the capital stock and labor force, respectively. Q_J is the level of human capital reached by vintage year J which can be utilized by the increment to the labor force in the production of additions to output. Equation (10), if it holds, implies that the coefficients of the production function (ignoring economies of scale) are the same whether one estimates the relation for increments to output or for levels of our [equation (9)].

Vintage effects, when included in an empirical specification, permit a test to determine whether productivity is greater for more recent additions to the capital stock. If interactions initially have an unsystematic effect, this obscures the production relation of changes in physical capital to increments in output for vintage years soon after the base year (that is, the start of the period examined). However, as the time elapsed from the base year increases, the production relation for increments to output approaches that for a specification in terms of levels rather than changes. A change in capital variable can thus be assumed to capture the "levels" effect of a balanced investment plan and, in addition, the systematic component of the impact of interactions on productivity.

IV. ESTIMATES OF EMBODIMENT FOR OLD PLANTS

Using cross-section data, we again estimate a modified Cobb-Douglas production function, this time for changes in output and in labor and capital inputs for old plants. The model is written as follows:

$$)\log O_{jt} = \$_{ot} + \$_{1t}\ )\log L_{jt} + \$_{2t} \log Q_{jt} + \$_{3t}\ )\log K_{jt} + \$_{4t} V_{jt} + u_{jt} \qquad (11)$$

where $)\log o_{jt}$ is the percentage change in the log of output for j^{th} plant for time t relative to the initial period of 1972, $)\log L$ is the percentage change in pure labor, and $)\log K$ is the percentage change in gross capital. Percentage changes standardize units to control for size effects across plants and, in a sense, also standardize the observations for differences in initial factor proportions.

Log Q measures the level of human capital available to the increment in the labor force, and V is, as before, a measure of the weighted average vintage of investment expenditures for each plant. Output is again measured by the (deflated) value of shipments or, alternatively, value added, labor by total employees, and labor quality or human capital by the average wage rate for each plant. The weights for vintage are, of course, the annual investment expenditures for the period over which changes in capital inputs are measured.

For <u>each</u> regression, the initial capital stock for each plant is simply its deflated gross assets in 1972, measured as described in the appendix, and the terminal capital stock is obtained by adding to the initial value cumulated (deflated) gross capital expenditures plus the capitalized value of the change in rentals of assets. Errors associated with the measurement of initial stocks, for which data on annual investment streams are lacking, can be expected to reduce greatly the goodness of fit of our model.

Our first objective was to test the implications of equation (8) that the power of interactions gradually declines over time. Equation (11) was therefore estimated consecutively for each year. According to the null hypothesis of no embodiment in the form of vintage or interaction effects, $\$_{4t} = 0$ and $\$_{3t} > 0$, respectively, in the years immediately following 1972. A positive and stable measured effect for the)log K variable would indicate relatively weak interaction effects, and, hence, a separable production relation for changes in output and capital input.

Our second objective was to derive estimates for all the variables in equation (11) that correspond to the production frontier and this required that we measure changes in output and inputs between points approximating capacity utilization. Production relations involving changes, as distinct from levels, of output and inputs are likely to be especially sensitive to the assumption of capacity utilization and that condition seems best approximated at output peaks.

For an empirical approximation of capacity utilization, the first peak was the higher of the 1972 and 1973 value of shipments. The second peak was the year with the highest value of shipments in the period 1983-86. The choice of time intervals within which the highest value was selected was not arbitrary. In the overwhelming majority of cases, the "true" peaks by almost any criterion did occur within those intervals.

The analysis was carried out with data for plants in 15 industries over the 1972-86 period. The criteria for selecting industries and plants are discussed in the appendix and the composition of industries is shown in Table A.

We now turn to results for the empirical model in equation (11), shown in Table 3. Table 3 is presented with shipments as the proxy for output. The same estimates but with value added as the dependent variable yielded very similar, though somewhat more erratic results with lower values of R^2. For economy of space, the latter are not reported in detail.

The results show the consecutive changes in coefficients for old plants for the <u>increments</u> in output and inputs from 1972 to the levels for each successive year. In general, there is strong support for the conclusion that for an extended period, interactions with the initial capital stock do not permit estimation of a separable relation between change in capital inputs and the change in output. It takes roughly twelve years for the relative effect of interactions to decline to a level that permits one to estimate a stable coefficient for the change in the log of K.

Table 3

PRODUCTION RELATIONS FOR CHANGES IN OUTPUT RELATIVE TO 1972
OLD PLANTS WITH POOLED DATA FOR 15 INDUSTRIES, 1973-86
(Numbers in parenthesis below the coefficients are t-values.)

Year	Intercept	L	Q	K	V	R^2	Sample Size
1973	-.190	.925	.081	-.054	-.008	.524	1402
	(-2.04)	(36.30)	(3.06)	(-1.58)	(-.32)		
1974	-.356	.991	.105	.020	.037	.545	1399
	(-3.19)	(34.94)	(3.10)	(.55)	(1.70)		
1975	-.409	.916	.144	.118	-.005	.581	1400
	(-3.50)	(36.76)	(4.01)	(3.72)	(-.33)		
1976	-.517	.849	.192	.206	-.004)	.565	1401
	(-4.24)	(33.04)	(5.23)	(6.67)	(-.26)		
1977	-.635	.862	.228	.199	.009	.565	1401
	(-4.46)	(32.75)	(5.38)	(6.23)	(.62)		
1978	-.274	.876	.121	.202	.002	.532	1404
	(-.174)	(28.90)	(2.59)	(5.87)	(.13)		
1979	-.347	.897	.155	.200	-.003	.546	1402
	(-2.17)	(30.26)	(3.24)	(6.00)	(-.28)		
1980	-.145	.950	.128	.224	-.054	.568	1404
	(-.90)	(31.35)	(2.50)	(6.22)	(-4.56)		
1981	-.264	.986	.070	.202	.025	.576	1403
	(-1.37)	(31.93)	(1.20)	(5.39)	(1.98)		
1982	-.316	.979	.062	.203	.036	.577	1403
	(-1.65)	(31.60)	(1.05)	(5.45)	(3.06)		
1983	-.781	.867	.203	.279	.039	.524	1403
	(-3.99)	(26.15)	(3.42)	(6.98)	(3.29)		
1984	-1.003	.816	.243	.337	.049	.531	1402
	(-4.95)	(24.34)	(3.96)	(8.34)	(4.29)		
1985	-1.111	.817	.277	.372	.041	.557	1392
	(-5.15)	(26.05)	(4.33)	(9.17)	(3.69)		
1986	-1.268	.825	.341	.336	.040	.493	1333
	(-5.14)	(22.38)	(22.38)	(7.61)	(3.45)		

Source: U. S. Bureau of the Census, LRD database.

Growth in output and in inputs are measured from 1972 except that physical capital is lagged half a year. L is measured by the change in the log of employees, Q by the log of the average wage rate, K by the change in the log of capital with K_0 the deflated initial gross assets for each plant and K_1 equal to K_0 plus cumulated capital expenditures and the change in the log of capitalized value of rentals, V is measured by the weighted average vintage of investments (with higher values for more recent investments). The dependent variable, growth in output, is measured by change in the log of shipments. The detailed measurement procedures are described in the text and the appendix.

Over time, the coefficient for)log K increases from near zero and insignificance in the early 1970's to a significant positive elasticity of above .03 by 1984. Initially, a systematic relation between growth in capital and in output is obscured by the unpredictable effects of interactions, given large variations across plants in the age and size of the endowments of capital at the outset of the period. But as the ratio of cumulated investment to initial capital rises, interaction effects become more systematic and the coefficient for)log K measurable.

Technical change embodied in capital is shown most directly by V. The insignificant results for V in earlier years were to be expected. If the effects of increments in capital are obscured by interactions, it is likely that so will the effects of changes in the vintage of capital. Moreover, since it is the vintage of post 1972 capital that was measured, sufficient time had to elapse for there to be enough dispersion in vintage to detect an effect.

Accordingly, the coefficient of V did not become significantly positive until 1982, but remained reasonable stable thereafter averaging .04 for the five year interval 1982-86. The approximately 4 percent increase in output for every one year change in vintage is substantially the same as that observed earlier for new plants. Thus the high rate of embodied technical change observed for new plants is confirmed with data for old plants.

The consistently rising negative value of the intercept a one moves from 1973 to 1986 is explained by the construction of the capital variable. While V measured changes in the vintage of post-1972 capital, no allowance was made for the progressive obsolescence of the initial (1972) stock of capital. Hence, for all plants, terminal year capital was systematically overstated by an increasing amount for each successive year. Thus the rising negative intercept appears to capture the obsolescence rate for old capital.

Table 3 gives us some insight into the effect of interactions between new and old inputs of physical capital. It is problematic, however, insofar as year-to-year changes may represent observations for less than capacity utilization and, hence, may not correctly measure the production frontier. This is especially a problem for the labor input and may explain the instability of th coefficient for log of Q in Table 3. As is well known, firms retain skilled labor during contractions in output. The resulting change in the composition of labor, with its consequent change in the average wage, is likely to lead to some distortion in the coefficients for L and Q. An illustration of this phenomenon is reflected in the non-significant results for Q during the 1981-82 recession.

V. COMPARING PRODUCTION RELATIONS FOR NEW AND OLD PLANTS

To avoid the problem of non-production frontier estimates in Table 3, equation (11) was estimated again for the same sample of old plants but limited to peak to peak changes, with initial and terminal peaks identified as indicated earlier. The resulting estimates, with both shipments and value added as proxies for output, were compared with the coefficients for new plants. The latter were derived from equation (5) but limited now to the same 15 industry sample as used for old plants. The estimates are shown in Table 4.

Before proceeding with the comparison of old and new plants, some characteristics of the results for old plants might be noted. As compared with the average coefficients reported in Table 3 for consecutive years, the coefficient for labor declines markedly. Those for physical capital and vintage rise though the order of magnitude remains roughly the same as before. In estimating an industry dummy variable model as for new plants in Section II, most of the industry dummies proved non-significant thereby rendering the coefficients for the aggregate more meaningful as average estimates.

Table 4

PRODUCTION RELATIONS FOR LEVELS FOR NEW PLANTS AND FOR CHANGES IN LEVELS FOR OLD PLANTS, POOLED DATA FOR 15 INDUSTRIES
(Numbers in parenthesis are t-values.)

New Plants

Dependent Variable	Intercept	L	Q	K	V	Adjusted R^2	Sample Size
Shipments	1.59 (7.48)	.66 (40.02)	.70 (10.39)	.31 (16.94)	.02 (1.94)	.84	1250
Value Added	.63 (2.62)	.63 (33.44)	.73 (9.59)	.30 (14.27)	.04 (4.39)	.78	1252

Old Plants

Dependent Variable	Intercept	L	Q	K	V	Adjusted R^2	Sample Size
Change in Shipments	-1.14 (-5.54)	.70 (19.7)	.26 (4.22)	.39 (9.80)	.05 (5.35)	.45	1404
Change in Value Added	- .76 (-2.59)	.78 (15.70)	.06 (.66)	.36 (6.39)	.06 (4.36)	.32	1405

Source: U.S. Bureau of the Census, LRD database.

The list of industries is shown in Table A. Growth in output and in inputs for old plants are measured from 1972 to 1973 except that physical capital is lagged half a year. Change in all inputs and output is measured from 1972 or 1973 (whichever had the higher output) to a year in 1984-1986 corresponding to an output peak. L is the log of total number of employees, and Q is the log of average wage rate. K for new plants is the log of cumulated capital expenditures plus the capitalized value of the change in rentals. For old plants it is the change in the log of capital with capital equal to K_0, the deflated initial gross assets for each plant, plus cumulated capital expenditures and the change in the capitalized value of rentals. V is measured by the weighted average vintage of investments (with higher values for more recent investments). The dependent variable output, is measured for new plants by the log of terminal year shipments or, alternatively, terminal year value added and for old plants by change in a the log of shipments or value added. The detailed measurement procedures are described in the text and the appendix.

Comparing the results in Table 4 we find:

(a) As to be expected, the R^2 values for new plants are much higher than for old plants--a fact attributable in large part to far superior data for the capital variable for new plants.

(b) For new plants, the coefficient for human capital (Q) is substantially higher than for old plants. The efficiency with which new plants use human capital appears to be their single most important advantage over old plants. Once technological options are limited by a large amount of old physical assets, the ability to substitute human capital for other inputs appears to be severly restricted.

(c) The coefficient for labor is of roughly the same magnitude for old and new plants.

(d) Especially important is the considerable stability in the coefficients for K when estimates based on changes in inputs and output for old plants are compared with levels for new plants. However, while these coefficients are generally of the same order of magnitude, the coefficients remain slightly higher for old plants. This may suggest some continued impact of interactions even after a period of as much as 14 years past the point at which the initial capital stock was measured.

(e) V continues to be much more sensitive than K to choice of sample and proxy for output. However, the higher estimates for old than for new plants are consistent with what we know about capital expenditures. A larger proportion of capital outlays are devoted to structures rather than to equipment for new than for old plants. Structures are generally assumed to be associated with much lower rates of obsolescence (hence, embodied technical change).

VI. SUMMARY

The principal results of this paper are now briefly summarized:

1. We first specified a production function with human capital as a separate argument and with embodied technical change proxied by a variable that measures the average vintage of the stock of capital.
2. The coefficients of the production function were first estimated with cross section data for roughly 2150 new manufacturing plants in 41 industries, and for subsets of this sample. An augmented Cobb-Douglas specification was used. The results proved fairly stable across varying samples of plants and with respect to alternative measures of output.
3. Substantively, it was found that the elasticity of output with respect to human capital was approximately the same as it was with respect to pure labor. Embodied technical change of capital produced an average 4 percent increase in output for each one year change in average vintage.
4. It was pointed out that most investment in a developed economy is made on old rather than on new plants. An important question, therefore, concerns the separability of the relation between new

inputs (that is, changes in the level of inputs) and changes in the level of output. A model was specified with interactions between new investment and initial endowments of capital. Interaction effects were predicted to decline in importance as a function of time.

5. Using a sample of roughly 1400 old plants in 15 industries, it was found that interactions between new investment and initial endowments of capital were, for a long interval of time, too unsystematic to permit measurement of a coefficient for capital. After twelve to fourteen years of cumulative investment, a systematic relation between changes in the level of inputs and changes in the level of output became measurable. Moreover, the coefficient for changes in the capital input for old plants proved to be of approximately the same magnitude as that for level of capital for new plants.

6. Comparing new and old plants over the "long-run," the estimates of embodied technical change of capital and of the elasticity of output with respect to number of employees (pure labor) proved very similar for the two types of plants. Differences between new and old plants in the elasticity of output with respect to human capital remained very large, however, and appear to be an important difference between the two sets of plants.

Appendix on Data Construction

Capital

For our measure of physical capital for new plants, we cumulated gross investment over the relevant interval (but lagged half a year), deflated by the implicit price deflator for capital expenditures in all manufacturing combined (the latter based on unpublished Bureau of Economic Analysis data).

There are opposing biases in using industry level deflators versus those for the economy as a whole for measuring in constant prices the value of the physical inputs that comprise the capital stock. If interindustry variations in input prices reflect mainly differential changes in scarcities, then industry level price deflators are to be preferred. But if interindustry price variations reflect mainly unmeasured changes in the quantities of inputs--for example, the quantity of human capital embodied in the labor inputs that enter into production of capital goods--then industry-level deflators are misleading. The best compromise seemed to us the use of manufacturing-wide deflators.

To the cumulative total of gross capital expenditure we added the capitalized value of the changes in rentals of fixed assets.[3] For our sample of industries and plants, the resulting addition was

---

[3] Rental payments for each plant are reported in our data base. The relevant change in value was capitalized by the average ratio of gross fixed assets to the sum of net income before taxes plus interest paid plus depreciation. Thus estimates were made for aggregate manufacturing for 1972-86, as reported in U.S. Internal Revenue Service, Statistics of Income.

relatively small. Finally, for most plants there was some initial capital stock that anteceded the birth of the plants in Census records. This stock had several origins: (a) from initial capital outlays preceding the recorded birth of the plant, (b) from the transfer of existing old assets to new activities following the recorded birth of the plant, (c) from the acquisition of old assets from other owners in the year preceding the plant's recorded birth. We assumed that (a) and (c) accounted for most of this initial stock and the appropriate deflator for it was, therefore, the capital expenditure deflator for the year preceding the plant's birth. In short, we assumed that the assets were generally acquired at market prices prevailing just prior to the plant's birth.

For old plants the measure of capital was less satisfactory as a full history of investment streams prior to the starting point for measuring changes was not available. The initial stock was therefore measured by gross fixed assets for each plant deflated by capital stock price deflators computed for 2-digit industries.[4] To the gross fixed assets we again added the capitalized value of rental payments for capital goods and again this addition was, in fact, relatively small. For measuring the change in capital inputs, we, of course, need the terminal value as well as the

[4] The deflators were derived from ratios of gross capital stocks at historical cost to stocks at constant cost as reported in Bureau of Economic Analysis, U.S. Department of Commerce, Fixed Reproducible Wealth in the United States, 1925-85, 1987.

initial value of the capital stock. This was achieved by adding to the initial capital stock the sum of gross investments over the relevant period, measured as for new plants, plus the capitalized value of the change in rental payments.

Labor and Human Capital

Labor input for each plant was measured by the Census record for its number of employees. An alternative measure, man-hours, was not used because it is available only for production workers. Our proxy for human capital, the average wage rate, was derived by dividing each plant's recorded wage bill by the number of employees.

Output

Output was proxied alternatively by data for shipments and for value added, each deflated by an appropriate deflator for the relevant 4-digit industry.[5]

Shipments data ignore variations across plants in purchases from other plants--hence in the degree of vertical integration. On the other hand, value added is subject to statistical error in the measurement of cost of materials, and errors arising from inconsistencies over time in the valuation of semi-finished and finished product inventories. The question of whether shipments or value added constitutes the better measure is an empirical one and

[5] The deflators were drawn from unpublished data of the Bureau of Economic Analysis and consisted of implicit deflators at the 4-digit level.

the answer is likely to differ depending on the sample of plants and industries one chooses.

New and Old Plants

As noted earlier, new as distinct from old plants were defined as plants born in 1973 or later. While the primary purpose of distinguishing between new and old plants was to separate plants with and without significant initial endowments of capital, there are also important other differences between the two sets of plants.

The record shows that new plants were considerably younger, by any criterion, than old plants. Further, for the new plants in our study, the bulk of their capital outlays were made within several years of their birth. This appears clear from the narrow spread for a 15 industry sample between the average age of plants since birth (which was roughly 8.5 years) and the weighted average age of their capital stock (which was 6.3 years with weights based on annual capital outlays).

Composition of Sample and Time Period Studied

For the analysis of new plants, two sets of industries were selected: one comprising 41 manufacturing industries and a subset of 32 industries. For the larger set, we included all industries with at least 16 new plants in 1982 (excepting only NEC industries and several that might not be considered primarily in manufacturing, e.g. publishing). For the subset of 32, the cutoff was 20 new plants.

For the analysis of old plants, and for comparisons of old and new plants, a further subset of 15 industries was employed. These consisted generally of the largest among the 41 but with selection based partly also on the desirability of broad representation across the industrial spectrum.

Within these sets of industries, only plants that satisfied the following criteria were chosen: (a) a continuous history in the same industry, from birth for new plants and from 1972 for old, until 1986, (b) a primary industry specialization ratio of at least 50 percent. This gave us about 2150 new plants for the 41 industries, roughly 1900 for the 32, and about 1250 for the 15. Our sample consisted of about 1400 old plants in the 15 industries.

The period chosen for analysis, 1972-86, was determined by the time interval for which panel data were available. The cross section analysis was for the terminal peak for each plant which was identified as the year with the highest value of shipments in the period 1984-86. For measuring change in inputs and output for old plants, an initial peak year had to be identified and this was chosen for each plant as either 1972 or 1973 depending on which was associated with higher shipments. The list of industries for the various samples is shown in Table A.

Table A

List of 41 Industries

SIC Code		Industry Name	Number of Plants in 1982
2011	+	Meatpacking Plants	25
2013	+	Sausages and Other Prepared Meat Products	36
2016	+	Poultry Dressing Plants	26
2022		Cheese, Natural and Processed	16
2026		Fluid Milk	18
2037		Frozen Fruits and Vegetables	16
2051	+	Bread, Cake, Related Products	32
2065	+	Confectionery Products	21
2086	*	Bottled and Canned Soft Drinks	33
2328		Men's and Boys' Work Clothing	16
2421	*	Sawmills, Planing Mills, General	94
2436		Softwood Veneer and Plywood	17
2451	*	Mobile Homes	31
2512	+	Upholstered Household Furniture	21
2653	*	Corrugated, Solid Fiber Boxes	34
2655		Fiber Cans, Drums, Similar Products	17
2752	*	Commercial Printing, Lithographic	48
2813	*	Industrial Gases	68
2821	+	Plastics Materials and Resins	20
2834		Pharmaceutical Preparations	18
2851	*	Paints and Allied Products	16
2911	*	Petroleum Refining	18
3357	+	Nonferrous Wiredrawing, Insulating	22
3411	*	Metal Cans	50
3441	*	Fabricated Structural Metal	32
3443	+	Fabricated Platework, Boiler Shops	21
3494	+	Valves and Pipe Fittings	26
3523	+	Farm and Garden Machinery	26
3531		Construction Machinery	17
3533	+	Oilfield Machinery	39
3544	+	Special Dies, Tools, Jigs, etc.	20
3561	+	Pumps and Pumping Equipment	22
3573	*	Electronic Computing Equipment	96
3585	*	Refrigeration, Heating Equipment	35
3612		Transformer	16
3613	+	Switchgear, Switchboard Apparatus	22

3621 +	Motors and Generators	26
3662 *	Radio, TV Communication Equipment	76
3674 *	Semiconductors, Related Devices	43
3714 *	Motor Vehicle Parts, Accessories	48
3731 +	Ship Building and Repairing	21

* 15 industry sample.
\+ 32 industry sample.

References

Becker, G. 1964. Human Capital, The University of Chicago Press.

Gort, M., and R. Boddy. 1967. "Vintage Effects and the Time Path of Investment in Production Relations," in The Theory and Measurement of Production Relations, Studies in Income and Wealth, Vol. 32, National Bureau of Economic Research.

Hall, R. E. 1968. "Technical Change and Capital From the Point of View of the Duel," Review of Economic Studies, XXXV, 35-46.

Prucha, I. R., and M. I. Nadiri. 1990. "Endogenous Capital Utilization and Productivity Measurement in Dynamic Factor Demand Models: Theory and an Application to the U.S. Electrical Machinery Industry," working paper.

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