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POST-WAR ECONOMIC GROWTH IN THE GROUP-OF-FIVE COUNTRIES: A NEW ANALYSIS

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ABSTRACT

An inter-country aggregate production function is estimated using annual data for the post-war period drawn from the Group-of-Five (G-5) countries: France, West Germany, Japan, United Kingdom and United States. It is assumed that all countries have the same underlying production function, not in terms of the measured outputs and inputs, but in terms of efficiency-equivalent units of outputs and inputs. The measured quantities of outputs and inputs of each country may be converted into efficiency-equivalent quantities of outputs and inputs by the multiplication of country and commodity-specific and time-varying augmentation factors. These augmentation factors are estimated simultaneously with the parameters of the aggregate production function.

Within this framework, the traditional assumptions for the measurement of productivity--constant returns to scale, neutrality of technical progress and profit maximization--are tested and all are rejected. Additional hypotheses about the nature of technical progress are also tested. It is found that technical progress may be represented as purely capital-augmenting. In particular, the rate of augmentation is estimated at between 14 and 16 percent per annum for France, West Germany and Japan, and between 8 and 10 percent per annum for the U.K. and the U.S. for the period under study. It is also found that technical progress is capital-saving rather than labor-saving and is therefore unlikely to be a cause of structural unemployment.

Using the estimated production function parameters, a growth-accounting exercise is carried out and the results are compared with those obtained from the conventional approach. Technical progress is found to be the most important source of growth, accounting for more than 50 percent, followed by the growth of capital input. Together they account for more than 75 percent of the growth of real output in the Group-of-Five (G-5) countries in the period under study. An international and intertemporal comparison of the productive efficiencies is also undertaken. It is found that the United States had the highest level of overall productive efficiency for the whole period under study. However, the productive efficiencies of France, West Germany and Japan rose rapidly from less than 40 percent of the U.S. level in 1949 to two-thirds of the U.S. level in 1985. There is thus some evidence of convergence.

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1. Introduction

The objective of this study is to apply a new approach to the analysis of post-war economic growth in the Group-of-Five (G-5) countries. The framework used provides meaningful comparisons of the levels *and* the rates of growth of productivities across countries. This new approach also enables us to identify separately not only the degree of returns to scale and the rate of technical progress in each country but also their biases, if any. The results of our empirical analysis are used as the basis for a new assessment of the relative contributions of capital, labor and technical progress to economic growth that does not depend on the conventional strong assumptions of growth accounting--constant returns to scale, neutrality of technical progress and profit maximization with competitive output and factor markets.

The new approach is based on the Lau-Yotopoulos (1989) modification of the concept of the meta-production function, introduced by Hayami and Ruttan (1970, 1985), through the use of time-varying, country- and commodity-specific augmentation factors. An empirical aggregate meta-production function is estimated from pooled inter-country time-series data. The basic assumptions for this factor-augmentation approach to the meta-production function are:

(1) All countries have the same underlying production function $F(\cdot)$ but may operate on different parts of it. The production function, however, applies to "efficiency"-equivalent quantities of outputs and inputs, that is:

$$(1.1) \qquad Y^*_{it} = F(X^*_{i1t}, \ldots, X^*_{imt}) \quad , \quad i = 1, \ldots, n \quad ;$$

where Y^*_{it} and X^*_{ijt}'s are the "efficiency"-equivalent quantities of output and inputs respectively of the ith country at time t, m is the number of inputs, and n is the number of countries. The assumption of a meta-production function implies that $F(\cdot)$ does not depend on i (but may depend on t).

(2) The "efficiency"-equivalent quantities of output and inputs of each country are not directly observable. They are, however, linked to the measured quantities of outputs, Y_{it}'s, and inputs, X_{ijt}'s, through time-varying, country- and commodity-specific augmentation factors $A_{ij}(t)$'s, $i = 1,\ldots,n$; $j = 0,\ldots,m$:

(1.2) $$Y^*_{it} = A_{i0}(t)Y_{it} \quad ;$$

(1.3) $$X^*_{ijt} = A_{ij}(t)X_{ijt} \quad , \quad j = 1,\ldots,m \quad .$$

We note that in terms of the <u>measured</u> quantities of outputs, the production function may be rewritten as:

(1.4) $$Y_{it} = A_{i0}(t)^{-1}F(X^*_{i1t},\ldots,X^*_{imt}), \; i = 1,\ldots,n,$$

so that the reciprocal of the output-augmentation factor $A_{i0}(t)$ has the interpretation of the possibly time-varying level of the technical efficiency of production, also referred to as output efficiency, in the ith country at time t.

There are many reasons why these commodity augmentation factors are not likely to be identical across countries. Differences in climate, topography and infrastructure; differences in definitions and measurements; differences in quality; differences in the composition of outputs; and differences in the technical efficiencies of production are some examples. The commodity augmentation factors are introduced precisely to capture these differences across countries. In this study, the commodity augmentation factors are assumed to have the exponential form with respect to time. Thus:

(1.5) $$Y^*_{it} = A_{i0} \exp(c_{i0}t)Y_{it} \quad ;$$

(1.6) $$X^*_{ijt} = A_{ij} \exp(c_{ij}t)X_{ijt} \quad , \quad j = 1,\ldots,m \quad , \quad i = 1,\ldots,n;$$

where the A_{i0}'s, A_{ij}'s, c_{i0}'s, and c_{ij}'s are constants. We shall refer to the A_{i0}'s and A_{ij}'s as <u>augmentation level</u> parameters and c_{i0}'s and c_{ij}'s as <u>augmentation rate</u> parameters. For at least one country, say the ith, the constants A_{i0} and A_{ij}'s can be set identically at unity (or some other arbitrary constants), reflecting the fact that "efficiency"-equivalent outputs and inputs can be measured only relative to some standard. Econometrically this means that the constants A_{i0}'s and A_{ij}'s cannot be uniquely identified without some normalization. Without loss of generality we take the A_{i0} and A_{ij}'s for the United States to be identically unity. The most important observation, however, is that the augmentation level and rate parameters are all potentially estimable subject to such a normalization--there is thus no need to rely on arbitrary assumptions or extraneous information. These country and commodity-specific augmentation level and rate parameters provide the basis for an international as well as intertemporal comparison of productive efficiencies. However, they may not be identifiable for an individual country if there is an insufficient number of observations. For example, with one output and two inputs, the number of augmentation level and rate parameters is increased by six for each additional country, hence a minimum of seven observations per country is required.

(3) The wide ranges of variation of the inputs resulting from the use of inter-country data necessitate the use of a flexible functional form for $F(\cdot)$ above. In addition, a flexible functional form is needed to allow the possibility of non-neutral returns of scale and technical progress.[1] In this study, the aggregate production function is specified to be the transcendental logarithmic (translog) functional form introduced by Christensen, Jorgenson and Lau (1973). For a production function with two inputs, capital (K) and labor (L), the translog production function, in terms of "efficiency"-equivalent output and inputs, takes the form:

$$(1.7) \qquad \ell n\, Y^*_{it} = \ell n\, Y_0 + a_k\, \ell n\, K^*_{it} + a_l\, \ell n\, L^*_{it} + B_{kk}(\ell n\, K^*_{it})^2/2 + B_{ll}(\ell n\, L^*_{it})^2/2 + B_{kl}(\ell n\, K^*_{it})(\ell n\, L^*_{it}) \quad .$$

Our new approach is applied to pooled inter-country time-series data. By pooling data across countries, the separate effects of economies of scale and technical progress, usually confounded by the simultaneous expansion of

[1]For example, if the meta-production function $F(\cdot)$ is chosen to be the Cobb-Douglas form, then the returns to scale will be neutral with respect to the inputs. Moreover, the commodity augmentation factors cannot be separately identified and thus the technology will be indistinguishable from one with neutral technical progress. For this last point, see, for example, Lau (1980).

scale with time in the data of a single country, can be more readily identified. (At any given point in time, production at different scales is observed. The same scale of production may be observed at different points in time.) In addition, such pooling allows the identification of not only the rates but also the biases of technical progress as well as the biases of the scale economies, if any. Moreover, inter-country data typically have greater variability in the quantities of inputs than intra-country data, thus facilitating the identification and estimation of the aggregate production function. For example, in data from a single country, the quantities of capital and labor are likely to move quite closely together, the consequence of a fairly constant capital-labor ratio, which may in turn be due to fairly stable relative prices. This multicollinearity may make it impossible to identify and estimate the effects of capital and labor separately without imposing some assumption such as constant returns to scale. With inter-country data, there is likely to be greater variability in the capital-labor ratio across countries, thus mitigating the possible effects of multicollinearity.

From a practical point of view, the primary advantage of our approach, which is based on the econometric estimation of an aggregate production function, is that it does not depend on the assumptions of constant returns to scale, neutral technical progress and profit maximization with competitive output and input markets, assumptions which underlie most growth accounting exercises. Instead, these assumption are directly tested.

In section 2, we present our model of a transcendental logarithmic production function with time-varying, country- and commodity-specific augmentation factors. In sections 3 and 4, we discuss the stochastic specification and the data respectively. Readers not interested in the technical details can skip to section 5, in which we report the results of our tests of hypotheses. The model estimates are presented in section 6. In section 7, we carry out a growth accounting exercise based on our estimates and compare our results with those using the conventional approach. In section 8, we undertake an international and intertemporal comparison of the productivities of the Group-of-Five countries based on our estimates. Finally, some concluding remarks are made in section 9.

2. The Model

We employ the transcendental logarithmic production function in equation (1.7). We do not assume constant returns to scale[2] or neutral technical progress.[3] We also do not assume instantaneous profit maximization with respect to capital or labor. Equation (1.7) is written in terms of the "efficiency"-equivalent quantities of output and inputs. By substituting equations (1.5) and (1.6) into equation (1.7), we obtain the translog production function in terms of measured quantities of output and inputs:

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[2]Most measurements of technical progress (or total factor productivity) assume constant returns to scale. However, it is an arbitrary assumption and the resulting estimate of technical progress is sensitive to the assumed returns to scale. In general, the higher the degree of returns to scale assumed, the lower the estimate of technical progress. Denison (1967) does not assume constant returns to scale. He assumes that the returns to scale are 1.1.

[3]Most measurements of technical progress (or total factor productivity) assume neutrality implicitly. Otherwise, such measurements of technical progress cannot be simply cumulated over time. Under non-neutral technical progress, the magnitude of technical progress depends on the quantities of the inputs.

$$(2.1)\quad \ell n\, Y_{it} = \ell n\, Y_0 - \ell n\, A_{i0} + a_k\, \ell n\, A_{iK} + a_l\, \ell n\, A_{iL}$$
$$+ B_{kk}(\ell n\, A_{iK})^2/2 + B_{ll}(\ell n\, A_{iL})^2/2 + B_{kl}(\ell n\, A_{iK})(\ell n\, A_{iL})$$
$$+ (a_k + B_{kk}\, \ell n\, A_{iK} + B_{kl}\, \ell n\, A_{iL})\ell n\, K_{it}$$
$$+ (a_l + B_{kl}\, \ell n\, A_{iK} + B_{ll}\, \ell n\, A_{iL})\ell n\, L_{it}$$
$$+ B_{kk}(\ell n\, K_{it})^2/2 + B_{ll}(\ell n\, L_{it})^2/2 + B_{kl}(\ell n\, K_{it})(\ell n\, L_{it})$$
$$+ (-c_{i0} + a_k c_{iK} + a_l c_{iL} + B_{kk}(\ell n\, A_{iK})c_{iK} + B_{kl}(\ell n\, A_{iL})c_{iK}$$
$$+ B_{ll}(\ell n\, A_{iL})c_{iL} + B_{kl}(\ell n\, A_{iK})c_{iL})t$$
$$+ (B_{kk}c_{iK} + B_{kl}c_{iL})(\ell n\, K_{it})t + (B_{kl}c_{iK} + B_{ll}c_{iL})(\ell n\, L_{it})t$$
$$+ (B_{kk}(c_{iK})^2 + 2B_{kl}c_{iK}c_{iL} + B_{ll}(c_{iL})^2)t^2/2 \quad ,$$

which simplifies into:

$$(2.2)\quad \ell n\, Y_{it} = \ell n\, Y_0 + \ell n\, A^*_{i0}$$
$$+ (a_k + B_{kk}\, \ell n\, A_{iK} + B_{kl}\, \ell n\, A_{iL})(\ell n\, K_{it})$$
$$+ (a_l + B_{kl}\, \ell n\, A_{ik} + B_{ll}\, \ell n\, A_{iL})(\ell n\, L_{it})$$
$$+ B_{kk}(\ell n\, K_{it})^2/2 + B_{ll}(\ell n\, L_{it})^2/2 + B_{kl}(\ell n\, K_{it})(\ell n\, L_{it})$$
$$+ c^*_{i0}t$$
$$+ (B_{kk}c_{iK} + B_{kl}c_{iL})(\ell n\, K_{it})t + (B_{kl}c_{iK} + B_{ll}c_{iL})(\ell n\, L_{it})t$$
$$+ (B_{kk}c_{iK}^2 + 2B_{kl}c_{iK}c_{iL} + B_{ll}c_{iL}^2)t^2/2 \quad ,$$

where A^*_{i0} and c^*_{i0} are country-specific constants. Equation (2.2) may be further simplified into:

$$(2.3) \quad \ln Y_{it} = \ln Y_0 + \ln A^*_{i0}$$
$$+ a^*_{ki} \ln K_{it} + a^*_{li} \ln L_{it}$$
$$+ B_{kk}(\ln K_{it})^2/2 + B_{ll}(\ln L_{it})^2/2 + B_{kl}(\ln K_{it})(\ln L_{it})$$
$$+ c^*_{i0} t$$
$$+ (B_{kk}c_{iK} + B_{kl}c_{iL})(\ln K_{it})t + (B_{kl}c_{iK} + B_{ll}c_{iL})(\ln L_{it})t$$
$$+ (B_{kk}c_{iK}{}^2 + 2B_{kl}c_{iK}c_{iL} + B_{ll}c_{iL}{}^2)t^2/2 \quad ,$$

where a^*_{ki} and a^*_{li} are also country-specific constants. Note that the only parameters that are independent of i, that is, of the particular individual country, are B_{kk}, B_{ll} and B_{kl}. They must be identical across countries. This provides a basis for testing the hypothesis that there is a single meta-production function for all the countries. The number of restrictions is 3(n-1) where n is the number of countries.

If the matrix of second-order parameters of the translog production function,

$$B = \begin{bmatrix} B_{kk} & B_{kl} \\ B_{kl} & B_{ll} \end{bmatrix} ,$$

is nonsingular, equation (2.3) may be further simplified by defining new parameters: let

$$(2.4) \qquad \begin{bmatrix} B_{ikt} \\ B_{ilt} \end{bmatrix} = B \begin{bmatrix} c_{iK} \\ c_{iL} \end{bmatrix}$$

then $(B_{kk}c_{iK}{}^2 + 2B_{kl}c_{iK}c_{iL} + B_{ll}c_{iL}{}^2)$

$$= [c_{iK}\ c_{iL}]B \begin{bmatrix} c_{iK} \\ c_{iL} \end{bmatrix}$$

$$= [B_{ikt}\ B_{ilt}]B^{-1}B\ B^{-1} \begin{bmatrix} B_{ikt} \\ B_{ilt} \end{bmatrix}$$

$$(2.5) \qquad = [B_{ikt}\ B_{ilt}]B^{-1} \begin{bmatrix} B_{ikt} \\ B_{ilt} \end{bmatrix} ,$$

so that equation (2.3) may be rewritten as:

$$
\begin{aligned}
(2.6) \qquad \ell n\, Y_{it} = {} & \ell n\, Y_0 + \ell n\, A^*_{i0} \\
& + a^*_{ki}\ \ell n\, K_{it} + a^*_{li}\ \ell n\, L_{it} \\
& + B_{kk}(\ell n\, K_{it})^2/2 + B_{ll}(\ell n\, L_{it})^2/2 + B_{kl}(\ell n\, K_{it})(\ell n\, L_{it}) \\
& + c^*_{i0}t \\
& + B_{ikt}(\ell n\, K_{it})t + B_{ilt}(\ell n\, L_{it})t \\
& + \frac{(B^2_{ikt}B_{ll} - 2B_{ikt}B_{ilt}B_{kl} + B^2_{ilt}B_{kk})}{(B_{kk}B_{ll} - B^2_{kl})}\ t^2/2
\end{aligned}
$$

Note that the parameter corresponding to the $t^2/2$ term for each country is not independent but is completely determined given B_{kk}, B_{kl}, B_{ll}, B_{ikt} and B_{ilt}. All the other parameters, given the hypothesis of a single meta-production function, are unrestricted. This provides a basis for testing the hypothesis of commodity augmentation. The number of restrictions is n where n is the number of countries.

Equation (2.3) or equivalently equation (2.6) is the most general specification possible under our maintained assumptions. We shall refer to this model as our "Base Model." It specializes to more restrictive forms under different hypotheses on (1) the returns to scale; (2) the nature of technical progress; and (3) the structure of technology.

Constant returns to scale of the production function implies that:

$$F(\lambda K, \lambda L, t) = \lambda F(K, L, t), \ \forall \ \lambda > 0, \ \forall \ K, \ L, \ t \ .$$

A necessary condition for constant returns to scale is homogeneity, which implies, for the translog production function:

$$(2.7) \qquad B_{kk} + B_{kl} = 0 \ ;$$

$$\text{and} \qquad B_{kl} + B_{ll} = 0.$$

The number of restrictions implied by homogeneity, given the hypotheses of a single meta-production function and commodity augmentation, is 2. Under homogeneity, the matrix B is singular and not all of the commodity augmentation factors can be uniquely identified. In particular, at most two out of the three commodity augmentation factors--output, capital and labor--can be uniquely identified for each country.[4] Thus, without loss of generality, we may take under homogeneity:

$$(2.8) \qquad A_{i0} = 1, \ \forall \ i \ ;$$

$$c_{i0} = 0, \ \forall \ i \ .$$

Under homogeneity, equation (2.1) simplifies into

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[4] For a discussion of this point, see Lau (1980).

$$(2.9)\quad \ell n\, Y_{it} = \ell n\, Y_0 + a_k\, \ell n\, A_{iK} + a_l\, \ell n\, A_{iL}$$
$$- B_{kl}(\ell n\, A_{iK} - \ell n\, A_{iL})^2/2$$
$$+ (a_k - B_{kl}(\ell n\, A_{iK} - \ell n\, A_{iL}))\ell n\, K_{it}$$
$$+ (a_l + B_{kl}(\ell n\, A_{iK} - \ell n\, A_{iL}))\ell n\, L_{it}$$
$$- B_{kl}(\ell n\, K_{it} - \ell n\, L_{it})^2/2$$
$$+ ((a_k c_{iK} + a_l c_{iL}) - B_{kl}(\ell n\, A_{iK} - \ell n\, A_{iL})(c_{iK} - c_{iL}))t$$
$$- B_{kl}(c_{iK} - c_{iL})(\ell n\, K_{it} - \ell n\, L_{it})t$$
$$- B_{kl}(c_{iK} - c_{iL})^2 t^2/2 \quad ,$$

which may be further simplified into:

$$(2.10)\quad \ell n\, Y_{it} = \ell n\, Y_0 + \ell n\, A^*_{i0}$$
$$+ a^*_{ki}\, \ell n\, K_{it} + (a^* - a^*_{ki})\ell n\, L_{it}$$
$$- B_{kl}(\ell n\, K_{it} - \ell n\, L_{it})^2/2$$
$$+ c^*_{i0} t$$
$$- B_{kl}(c_{iK} - c_{iL})(\ell n\, K_{it} - \ell n\, L_{it})t$$
$$- B_{kl}(c_{iK} - c_{iL})^2 t^2/2 \quad ,$$

where $a^* \equiv a_k + a_l$ $(\equiv a^*_{ki} + a^*_{li})$ is the degree of returns to scale which turns out to be identical across countries and $c^*_{i0} \equiv a^*_{ki}(c_{iK} - c_{iL}) + a^* c_{iL}$. We note that $\ell n\, A_{iK}$, $\ell n\, A_{iL}$, c_{iK} and c_{iL} can be separately identified for each country, subject to a normalization of the A_{ij}'s. Constant returns to scale, conditional on the validity of the hypotheses of a single meta-production function and commodity augmentation, further imply that:

(2.11) $$a^* = a_k + a_l - 1 \quad .$$

Under this additional restriction, equation (2.10) becomes:

(2.12)
$$\begin{aligned}
&\ell n\ Y_{it} - \ell n\ L_{it} \\
&= \ell n\ Y_0 + \ell n\ A^*_{i0} + a^*_{ki}(\ell n\ K_{it} - \ell n\ L_{it}) \\
&\quad - B_{kl}(\ell n\ K_{it} - \ell n\ L_{it})^2/2 \\
&\quad + (c_{iL} + a^*_{ki}(c_{iK} - c_{iL}))t \\
&\quad - B_{kl}(c_{iK} - c_{iL})(\ell n\ K_{it} - \ell n\ L_{it})t \\
&\quad - B_{kl}(c_{iK} - c_{iL})^2\ t^2/2
\end{aligned}$$

The number of additional restrictions implied by constant returns to scale is 1.

Neutrality of technical progress of the production function $F(K,L,t)$ implies that:

(2.13) $$F(K,L,t) = F(F_0(K,L),t).$$

In other words, the marginal rate of substitution between capital and labor is, for given quantities of capital and labor, independent of time:

(2.14) $$\frac{\partial}{\partial t}\left(\frac{\frac{\partial F}{\partial K}(K,L,t)}{\frac{\partial F}{\partial L}(K,L,t)}\right) = 0, \qquad \forall\ K,\ L,\ t.$$

For the translog production function under the commodity augmentation hypothesis, neutrality of technical progress implies:

$$(2.15)\qquad \frac{\partial}{\partial t}\left(\frac{\dfrac{\partial \ln F}{\partial \ln K_{it}}}{\dfrac{\partial \ln F}{\partial \ln L_{it}}}\right)$$

$$= \frac{\partial}{\partial t}\left[\frac{(a_k+B_{kk}\ \ln A_{iK}+B_{kl}\ \ln A_{iL}) + B_{kk}\ \ln K_{it} + B_{kl}\ \ln L_{it} + (B_{kk}c_{iK}+B_{kl}c_{iL})t}{(a_l+B_{kl}\ \ln A_{iK}+B_{ll}\ \ln A_{iL}) + B_{kl}\ \ln K_{it} + B_{ll}\ \ln L_{it} + (B_{kl}c_{iK}+B_{ll}c_{iL})t}\right]$$

$$= 0\ .$$

In order for equation (2.15) to hold for all K, L and t, one must have:

$$(2.16)\qquad (a_l+B_{kl}\ \ln A_{iK}+B_{ll}\ \ln A_{iL})(B_{kk}c_{iK}+B_{kl}c_{iL})$$
$$= (a_k+B_{kk}\ \ln A_{iK}+B_{kl}\ \ln A_{iL})(B_{kl}c_{iK}+B_{ll}c_{iL});$$

$$B_{kl}(B_{kk}c_{iK}+B_{kl}c_{iL}) = B_{kk}(B_{kl}c_{iK}+B_{ll}c_{iL});$$

$$B_{ll}(B_{kk}c_{iK}+B_{kl}c_{iL}) = B_{kl}(B_{kl}c_{iK}+B_{ll}c_{iL}).$$

$(B_{kk}c_{iK}+B_{kl}c_{iL})$ is either zero or different from zero. If it were zero, then by equation (2.16) either $a_k = B_{kk} = B_{kl} = 0$, which implies that the marginal product of capital is zero for all K, L, t (at least in an open neighborhood of some K, L, t); or $(B_{kl}c_{iK}+B_{ll}c_{iL}) = 0$. The case of zero marginal product of capital (or, by symmetry, of labor) can be ruled out. We conclude that we must have either

$$(2.17) \qquad B_{kk}c_{iK} + B_{kl}c_{iL} = 0$$

$$\underline{\text{and}} \quad B_{kl}c_{iK} + B_{ll}c_{iL} = 0 \quad ;$$

or $(B_{kk}c_{iK}+B_{kl}c_{iL}) \neq 0$ <u>and</u> $(B_{kl}c_{iK}+B_{ll}c_{iL}) \neq 0$. If the matrix B were non-singular, then equation (2.17) implies that $c_{iK} = c_{iL} = 0$. If the matrix B were not non-singular, then equation (2.17) implies:

$$(2.18) \qquad B_{kk} = -B_{kl}c_{iL}/c_{iK} \quad ; \quad B_{ll} = -B_{kl}c_{iK}/c_{iL} \; .$$

We note that equation (2.18) imposes restrictions, not only on the nature of technical progress but also on the technology of the meta-production function. Moreover, since the B_{ij}'s are common to all countries, so must be c_{iK}/c_{iL}. Under the restrictions of equation (2.18), equation (2.2) takes the form:

$$(2.19) \qquad \ell n\, Y_{it} = \ell n\, Y_0 + \ell n\, A^*_{i0}$$
$$+ (a_k - B_{kl}c_L/c_K(\ell n\, A_{iK} - c_K/c_L \;\ell n\, A_{iL}))\; \ell n\, K_{it}$$
$$+ (a_l + B_{kl}(\ell n\, A_{iK} - c_K/c_L \;\ell n\, A_{iL}))\; \ell n\, L_{it}$$
$$+ B_{kl}c_L/c_K(\ell n\, K_{it})^2/2 - B_{kl}c_K/c_L(\ell n\, L_{it})^2/2$$
$$+ c^*_{i0}t$$

which is actually even more restrictive than the restrictions of $c_{iK} = c_{iL} = 0$, which, after all, do not place any restrictions on the a^*_{ji}'s and B_{ij}'s. We also note that $\ell n\, A_{iK}$ and $\ell n\, A_{iL}$ cannot be separately identified.

If $(B_{kk}c_{iK}+B_{kl}c_{iL}) \neq 0$ and $(B_{kl}c_{iK}+B_{ll}c_{iL}) \neq 0$, then equation (2.16) implies:

$$(2.20) \qquad a_k/a_l = B_{kk}/B_{kl} = B_{kl}/B_{ll} = (B_{kk}c_{iK}+B_{kl}c_{iL})/(B_{kl}c_{iK}+B_{ll}c_{iL}),$$

so that:

$$(2.21) \qquad \frac{\dfrac{\partial \ \ln F}{\partial \ \ln K_{it}}}{\dfrac{\partial \ \ln F}{\partial \ \ln L_{it}}} = \frac{a_k + B_{kk} \ \ln A_{iK} + B_{kl} \ \ln A_{iL}}{a_l + B_{kl} \ \ln A_{iK} + B_{ll} \ \ln A_{iL}} = \frac{a_k}{a_l}, \ \forall \ K_{it}, L_{it}, t.$$

We note that given the hypotheses of a single meta-production function and commodity augmentation, the first two restrictions of equation (2.20) imply the last one. Thus, the translog production function takes the form:

$$\begin{aligned}
(2.22) \qquad \ln Y_{it} &= \ln Y_0 + \ln A^*_{i0} \\
&+ (a_k+B_{kl}a_k/a_l \ \ln A_{iK}+B_{kl} \ \ln A_{iL})\ln K_{it} \\
&+ (a_l+B_{kl} \ \ln A_{iK}+B_{kl}a_l/a_k \ \ln A_{iL})\ln L_{it} \\
&+ B_{kl}(a_k/a_l(\ln K_{it})^2/2 + a_l/a_k(\ln L_{it})^2/2 + (\ln K_{it})(\ln L_{it})) \\
&+ B_{kl}(a_k/a_l c_{iK}+c_{iL})(\ln K_{it})t + B_{kl}(c_{iK}+a_l/a_k c_{iL})(\ln L_{it})t \\
&+ B_{kl}(\frac{a_k}{a_l} c_{iK} + c_{iL})(c_{iK} + \frac{a_l}{a_k} c_{iL})t^2/2 \\
&= \ln Y_0 + \ln A^*_{i0} \\
&+ (a_k + B_{kl}a_k/a_l(\ln A_{iK} + a_l/a_k \ \ln A_{iL}))\ln K_{it} \\
&+ (a_l + B_{kl}(\ln A_{iK} + a_l/a_k \ \ln A_{iL}))\ln L_{it} \\
&+ B_{kl}(a_k/a_l(\ln K_{it})^2/2 + a_l/a_k(\ln L_{it})^2/2 + (\ln K_{it})(\ln L_{it}))
\end{aligned}$$

$$+ B_{kl} a_k / a_l (c_{iK} + a_l / a_k c_{iL})(\ell n\ L_{it}) t + B_{kl} (c_{iK} + a_l / a_k c_{iL})(\ell n\ L_{it}) t$$
$$+ B_{kl} a_k / a_l (c_{iK} + a_l / a_k c_{iL})^2 t^2 / 2 .$$

We note that neither $\ell n\ A_{iK}$ and $\ell n\ A_{iL}$ nor c_{iK} and c_{iL} can be separately identified. Without loss of generality we may set:

$$(2.23) \qquad \ell n\ A_{iL} = 0 \ , \quad \forall\ i;$$
$$c_{iL} = 0 \ , \quad \forall\ i .$$

Moreover, equation (2.22) may be recognized to be simply a transformation of a Cobb-Douglas function. (This is also apparent from equation (2.21)). We conclude that in order for neutrality of technical progress to hold, either,

$$(2.24) \qquad c_{iK} = c_{iL} = 0 \ , \quad \forall\ i \ ;$$

or, the production function must be a generalized Cobb-Douglas production function, with the restrictions given in equation (2.20). The number of restrictions implied by equation (2.24) is $2n$. Under these restrictions, equation (2.3) becomes

$$(2.25) \qquad \ell n\ Y_{it} = \ell n\ Y_0 + \ell n\ A^*_{i0}$$
$$+ a^*_{ki}\ \ell n\ K_{it} + a^*_{li}\ \ell n\ L_{it}$$
$$+ B_{kk} (\ell n\ K_{it})^2/2 + B_{ll} (\ell n\ L_{it})^2/2 + B_{kl} (\ell n\ K_{it})(\ell n\ L_{it})$$
$$- c_{i0} t \ .$$

The number of additional <u>independent</u> restrictions implied by equation (2.20), conditional on a single meta-production function and commodity augmentation, is 2. We shall refer to the restrictions in equation (2.24) as the neutrality of technical progress restrictions and the restrictions in equation (2.20) as generalized Cobb-Douglas production function restrictions, to be tested as an hypothesis on the structure of technology.

In addition to the aggregate production function, we also consider the behavior of the share of labor costs in the value of output: $w_{it}L_{it}/p_{it}Y_{it}$, where w_{it} is the nominal wage rate and p_{it} is the price of output in the ith country at time t. Under competitive output and input markets, the assumption of profit maximization with respect to labor, which is a necessary condition for overall profit maximization, implies that the elasticity of output with respect to labor is equal to the share of labor cost in the value of output:

$$(2.26) \qquad \frac{w_{it}L_{it}}{p_{it}Y_{it}} = \frac{\partial \ell n \, Y_{it}}{\partial \ell n \, L_{it}}$$

$$= a_{li}^{*} + B_{kl} \, \ell n \, K_{it} + B_{ll} \, \ell n \, L_{it} + B_{lt} t \, .$$

In other words, the parameters in equation (2.26) are identical to the corresponding ones in equation (2.6). If we do not maintain the hypothesis of profit maximization with respect to labor, the parameters in equation (2.26) do not necessarily have to be the same as those in the aggregate production function. Equation (2.26) may be written in the form:

(2.27) $$\frac{w_{it}L_{it}}{p_{it}Y_{it}} = a_{li}^{**} + B_{kli}\ \ln K_{it} + B_{lli}\ \ln L_{it} + B_{lit}^{*}t\ .$$

Profit maximization with respect to labor then implies:

(2.28) $$a_{li}^{**} = a_{li}^{*};\ \forall\ i\ ;$$
$$B_{kli} = B_{kl}\ ;\quad B_{lli} = B_{ll};\ \forall\ i\ ;$$
$$B_{ilt}^{*} = B_{ilt};\ \forall\ i\ .$$

This provides a basis for testing the hypothesis of profit maximization with respect to labor. The number of restrictions implied by profit maximization with respect to labor is 4n.

Constant returns to scale, neutrality of technical progress and profit maximization are the three principal maintained hypotheses in the empirical measurement of total factor productivity (or equivalently technical progress). We test these three hypotheses in parallel, conditional on the hypotheses of a single meta-production function (identical second-order production function parameters) and a commodity augmentation form of technical progress.

Next, we proceed to examine hypotheses on the nature of technical progress. First, with respect to the augmentation level parameters, we test whether they are the same across the different countries separately for capital and labor. Given our normalization of A_{USK} and $A_{USL} = 1$, the hypotheses of identical augmentation level parameters are thus represented by respectively:

$$(2.29) \qquad \ell n\, A_{iK} = 0,\ \forall\, i \quad ; \text{ and}$$

$$(2.30) \qquad \ell n\, A_{iL} = 0,\ \forall\, i \quad .$$

The number of restrictions is equal to (n-1) for each of the hypotheses. If either or both hypotheses are rejected, we proceed to test whether the augmentation level parameters are identical across the European countries--France, West Germany and U.K.--within our sample separately for capital and labor. The hypothesis of equal augmentation level parameters across countries must be interpreted carefully because differences in definitions and measurements, in addition to differences in the underlying qualities, will also show up as differences in the estimated augmentation level parameters.

Second, with respect to the augmentation rate parameters, we begin by testing the hypothesis of whether technical progress can be adequately represented by two rather than three augmentation rates. (Note that if the hypothesis of homogeneity is accepted, it automatically implies that technical progress can be represented by two rates.) We test the two-rate hypothesis by testing separately the hypotheses that the augmentation rates for output, capital, and labor are respectively equal to zero. If all of the three separate component hypotheses are rejected, then technical progress cannot be represented by only two rates. If any one of them is not rejected, the hypothesis that technical progress can be adequately represented by two rates is not rejected.

If the two-rate hypothesis is not rejected, we proceed to test whether technical progress can be adequately represented by a single augmentation rate. We test the one-rate hypothesis by testing separately the hypotheses that pairs of the augmentation rates of output, capital, and labor are equal to zero. There are three such possible pairs of zero rates. If all of the three separate component hypotheses are rejected, then technical progress cannot be represented by only a single rate. If any of them is not rejected, then technical progress can be adequately represented by a single rate.

The two-rate hypothesis takes the form:

(2.31) Either $c_{i0} = 0;\ \forall\ i$;

or $c_{iK} = 0;\ \forall\ i$;

or $c_{iL} = 0;\ \forall\ i$.

In other words, at least one of the three sets of augmentation rate parameters are equal to zero. The one-rate hypothesis takes the form:

(2.32) Either $c_{i0} = c_{iK} = 0;\ \forall\ i$

or $c_{i0} = c_{iL} = 0;\ \forall\ i$;

or $c_{iK} = c_{iL} = 0;\ \forall\ i$.

We note that the restrictions implied by the last alternative are identical with those implied by neutrality of technical progress.

Depending on the outcome of the tests of the two-rate and one-rate hypotheses, we proceed to test whether the augmentation rate parameters are identical across all countries or across European countries. The hypothesis of equal augmentation rate parameters across countries must likewise be interpreted carefully because they may reflect changes in the definitions, measurements (e.g. depreciation rates), utilization rates, and improvements in the quality of complementary inputs over time, in addition to changes in the underlying quality of the inputs. Moreover, one cannot in general associate an improvement in the quality of an input with an increase in its augmentation factor. For example, an increase in the number of individuals who can type may show up as an augmentation of capital (an increase in the effective number of typewriters) rather than labor. Better roads may also show up as an augmentation of capital (an increase in the effective number of vehicles).

Finally, one may be interested in hypotheses on the structure of technology. We proceed to test first the hypothesis that the meta-production function is of the Cobb-Douglas form, which implies $B_{kk} = B_{ll} = B_{kl} = 0$, a total of 3 restrictions. Under the Cobb-Douglas hypothesis, only a single augmentation factor can be identified. (However, the Cobb-Douglas hypothesis is certain to be rejected if the hypothesis of homogeneity is rejected.) We test next the hypothesis that the production function is of the generalized Cobb-Douglas form, which implies the independent restrictions in equation (2.20), a total of 2 restrictions. Under the generalized Cobb-Douglas hypothesis, only two augmentation factors can be identified. The Cobb-Douglas and the generalized Cobb-Douglas hypotheses do not imply each other and are tested in parallel.

3. The Stochastic Specification

We introduce stochastic disturbance terms ϵ_{1it}'s and ϵ_{2it}'s into the

Labor is measured as the number of person-hours worked. The labor supply of the economy is measured by the civilian labor force. The data are taken from Labor Force Statistics (1968, 1986) published by the OECD except for the period of 1948-1955 for the United States, data for which are estimated by splicing the published data on civilian labor force from the U.S. Department of Commerce, Historical Statistics of the United States, Colonial Times to 1970 to those of Labor Force Statistics. Unemployment rates are obtained from the same sources. Employment is estimated as the labor force times one minus the unemployment rate. It is then multiplied to the average number of hours worked per year to obtain labor hours.

The share of labor in the value of output is estimated by dividing the current labor income (compensation of employees paid by resident producers) by the current GDP of each country, data for which are obtained from OECD, National Accounts, except for the period 1948-1955 for the United States. Current labor income data for the United States for this period are obtained from National Income and Product Accounts of the United States, U.S. Department of Commerce and GDP in current prices are obtained from Survey of Current Business, 1980. The compensation of employees paid by resident producers includes "all payments by resident producers of wages and salaries to their employees, in kind and in cash, and of contributions, paid or imputed, in respect of their employees to social security schemes and to private pension, family allowance, casualty insurance, life insurance and similar schemes."

(3) Capital (K)

Capital is measured as utilized capital. Gross fixed capital stock at the beginning of the year is used as a measure of capital supply. The data in 1980 prices are taken from OECD, Flows and Stocks of Fixed Capital, 1955-80 and 1960-85 except for U.S. (1948-55) and Japan (1957-63); the former is taken from BEA, Survey of Current Business, 1986, while the latter is based on Table 1-2 from Denison and Chung (1976). For Japan and the United States, the gross fixed capital stock data include only private non-residential capital. For France, the data include private non-residential and public capital.[6] For West Germany and the United Kingdom, the data include private non-residential, private residential and public capital. These data are converted into U.S. dollars using 1980 exchange rates. The data on capacity utilization are also taken from OECD, Main Economic Indicators: Historical Statistics (1960-79, 1964-1983) and Main Economic Indicators (1986) with the exception of U.S., U.K., Japan (1957-59) and France (1957-61). For Japan and France, the missing data are estimated by backward extrapolation. Capacity utilization rates for the U.S. are obtained from the Economic Report of the President, 1989. Capacity utilization rates for the U.K. are constructed by the peak-to-peak method. The estimated utilization rates for U.K. (average of 98.81 percent) are much higher than those for the other countries (average of 81.13 percent), because of the different methodologies used. In order to maintain comparability of the data, the estimated utilization rates for U.K. are multiplied by the ratio 81.13/98.81. Utilized capital is estimated as the capital stock at the beginning of the year times the capacity utilization rate.

[6] The original data for 1957-1965 include only private non-residential capital but have been adjusted so that they are comparable to data including both private non-residential capital and public capital.

(4) Time (t)

Time is measured in years chronologically with the year 1970 being set equal to zero.

(5) Instrumental Variables

The instrumental variables used in the estimation include: real output lagged one and two periods; lagged capital stock; lagged labor force; country dummies; world population; female life expectancy; male life expectancy; female population; male population; arable land; land under permanent crops; world prices of cotton, oil and iron ore relative to the world price of wheat; lagged relative prices of cotton, oil and iron ore; and time. For the first-differenced model, the actual instrumental variables employed consist of first differences of the natural logarithms of the continuous variables listed above as well as the dummy variables listed above. Data on world population are obtained from United Nations, Statistical Yearbook and female and male populations are obtained from OECD, Labor Force Statistics (1970, 1987). Female and male life expectancy are taken from United Nations, Demographic Yearbook. Data for land are obtained from Food and Agriculture Organization, Production Yearbook. The prices of cotton (Egypt Long Staple), oil (Venezuela-Tia Juana), iron ore (Brazil North Sea Ports), and wheat (Australia-Sydney) are obtained from International Monetary Fund, International Financial Statistics Yearbook (1979, 1989).

5. Empirical Results--Test of Hypotheses

The results of the nonlinear instrumental variables estimation indicate that the non-first-differenced model has a Durbin-Watson statistic that is close to unity for the labor share equation (1.03), suggesting serious mis-specification. The first-differenced model, however, has Durbin-Watson statistics that are much more reasonable--1.94 for the aggregate production function and 1.83 for the labor share equation. Thus we present only the results from the first-differenced model.

We first undertake a series of tests of hypotheses. We use as our criterion function the weighted sum of squares of residuals of the system of equations projected in the space spanned by the instrumental variables. Asymptotically, the difference between the weighted sum of squares with and without the restrictions implied by the null hypothesis is distributed as the χ^2 distribution with the appropriate degrees of freedom under the null hypothesis. These are the test-statistics used in this study. We choose as the overall level of significance for our study $\alpha = 0.10$. We assign different levels of significance to the different (groups of) hypotheses of interest so that their sum is 0.10, which assures that the overall level of significance of our study is at least 0.10. The test statistics for the different null hypotheses are presented in Tables 5.1 through 5.3.

The Maintained Hypotheses of the Study

We first test the basic maintained hypothesis of our study, namely that the aggregate production functions of all five countries are identical in terms of "efficiency"-equivalent inputs, that is, there is a single meta-production function. We assign a level of significance of 0.01 to this hypothesis. The test-statistic, χ^2 divided by the degrees of freedom, has a value of 0.78, with 12 degrees of freedom. This hypothesis cannot be rejected at any level of significance.

We next test the hypothesis that technical progress can be represented in the commodity-augmentation form with each augmentation factor being an exponential function of time conditional on the single meta-production function hypothesis. We assign a level of significance of 0.01 to this hypothesis. The test-statistic has a value of 0.31 with 5 degrees of freedom. This hypothesis cannot be rejected at any level of significance.

The non-rejection of these two hypotheses lends empirical support to the validity of the meta-production function with commodity augmentation factors approach adopted in this study.

Conventional Maintained Hypotheses

We then proceed to test the hypotheses maintained under conventional approaches to the measurement of total factor productivity and technical progress, conditional on the validity of our maintained hypotheses of a single meta-production function and commodity augmentation. We assign a level of significance of 0.02 to this series of tests, allocating it equally among the tests of homogeneity of the production function,[7] constant returns to scale of the production function, neutrality of technical progress, and profit maximization with respect to labor.[8] We find that all of these hypotheses can be separately rejected at their assigned levels of

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[7]Note that the restrictions implied by homogeneity are a subset of the restrictions implied by constant returns to scale. If homogeneity is rejected, constant returns to scale will be rejected at the same level of significance.

[8]In the first differenced form, the parameters a_{1i}^{**}'s of the labor share equation are not estimated. Thus, the hypothesis of profit maximization implies restrictions on only 3n, or 15 parameters.

significance, 0.005.[9] This series of tests suggest that the conventional approach to the measurement of total factor productivity and technical progress may be based on false premises, at least for the countries and time periods under study.

The results of these tests are presented in Table 5.1. In Table 5.4, the critical values of the test-statistics for alternative values of the level of significance are presented. The reader may wish to select alternative levels of significance for particular hypotheses.

Having established the validity of our current approach, we proceed to explore the nature of technical progress. We test whether: (1) augmentation level parameters are identical across countries; (2) technical progress can be represented by two sets of augmentation rates; and finally (3) technical progress can be represented by a single set of augmentation rates for output or an input. The purpose of these tests is to establish the levels, rates and biases of technical progress as well as to obtain a parsimonious specification. Under the commodity-augmentation hypothesis the number of independent parameters required to represent technical progress is 6 per country. The question is whether a smaller number will suffice. It should be noted that under the hypothesis of homogeneity of the production function, technical progress can always be represented by two sets of augmentation rate parameters. However, the hypothesis of homogeneity is quite decisively rejected in this study as evidenced in Table 5.1.

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[9] The hypothesis of profit maximization with respect to labor can be tested separately for each country. The test-statistics are 2.23, 1.87, 13.15, 1.97 and 1.40 for France, West Germany, Japan, U.K. and U.S. respectively. However, this does not imply that the hypothesis can be accepted for all countries except Japan because the α_{1i}^{**}'s turn out to be very different from the α_{1i}^{*}'s. See the discussion in Section 8 and Table 8.2.

We assign a level of significance of 0.01 to each group of hypotheses on the nature of technical progress. For the equality of augmentation level parameters across countries, we allocate 0.005 each for capital and labor respectively. We find that we cannot reject the hypothesis of identical capital augmentation level parameters across countries at any level of significance. We also cannot reject the hypothesis of identical labor augmentation level parameters across countries at the assigned level of significance. This implies that in the base year (1970), the "efficiencies" of capital and labor were not significantly different across countries. In fact, because the definitions of the capital stocks are the least inclusive for Japan and the United States and the most inclusive for West Germany and U.K., it implies that the efficiencies of capital are highest in Japan and the United States, followed by France and then West Germany and U.K. in the base year.

Next, we test the null hypothesis that technical progress can be represented by two (instead of three) sets of augmentation rates, that is, at least one set of augmentation rate parameters are zero. For this hypothesis, we examine the three separate component hypotheses, namely, that the set of output, capital, and labor augmentation rate parameters are respectively zeroes. The null hypothesis is true if and only if <u>at least</u> one of the three component hypotheses is true. Let the desired level of significance of the two-rate hypothesis be set at α. The probability of falsely rejecting this hypothesis when it is true is thus α. The decision rule that is adopted is that if <u>all</u> of the three component hypotheses are separately rejected at the same level of significance, say α^*, then the null hypothesis as a whole is rejected at a level of significance of α.

The question is, at what level should $\alpha*$ be set? It turns out that $\alpha*$ should be set equal to α.

The reasoning is as follows. The null hypothesis is that <u>at least</u> one of the three sets of augmentation rate parameters are equal to zero. If only one set of parameters are actually zero, then the probability of falsely rejecting the null hypothesis is exactly equal to $\alpha*$. If two sets are actually zero, then the probability of falsely rejecting the null hypothesis, under the adopted decision rule, is less than or equal to $\alpha*^2$. If all three sets are actually zero, then the probability of falsely rejecting the null hypothesis is less than or equal to $\alpha*^3$. In any event, the level of significance is less than or equal to $\alpha*$. By setting $\alpha* = \alpha$, the level of significance of the null hypothesis is guaranteed to be at least α. Thus, each one of the component hypotheses is allocated a level of significance equal to 0.01. At this level of significance, the null hypothesis of two rates cannot be rejected.

As the two-rate hypothesis is not rejected, we proceed to test the null hypothesis that technical progress can be represented by a single (instead of two) set of augmentation rate parameters. For this hypothesis, we again examine the three separate component hypotheses, namely, that the sets of output and capital, output and labor, and capital and labor augmentation rate parameters are respectively zeroes. Technical progress in these "one-rate" models may be identified as Harrod-neutral, Solow-neutral, and Hicks-neutral technical progress respectively. As in the two-rate case, each component hypothesis is allocated a level of significance equal to 0.01. At this level of significance, we reject the hypotheses of zero output and capital rates and zero capital and labor rates,[10] but we cannot reject the hypothesis of zero output and labor rates. We conclude that technical progress can be represented by a single set of augmentation rates for capital, that is, technical progress is capital-augmenting.

Having determined that technical progress can be represented as capital-augmenting, we proceed to test whether the capital augmentation rate parameters are identical across countries. (We do not need to test whether the output and labor augmentation rates are identical across countries because the hypothesis of zero output and labor augmentation rates cannot be rejected.) The hypothesis of identical capital augmentation rate parameters across countries, conditional on the maintained hypothesis of the study and the hypothesis of zero output and labor augmentation rate parameters, can be rejected at the assigned level of significance. The results of this series of tests are presented in Table 5.2.

European Communality

Another series of hypotheses of interest have to do with whether a certain group of countries, specifically European countries, have identical augmentation level and rate parameters. We assign a level of significance of 0.01 to this series of tests, to be allocated equally between identical augmentation levels and identical augmentation rates, which are further allocated proportionately among the component hypotheses within each group.

The hypotheses of identical augmentation level parameters for European

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[10]This hypothesis is in fact identical to that of neutrality.

countries cannot be rejected for both capital and labor.[11] The hypotheses of identical augmentation rate parameters for capital for European countries, conditional on zero output and labor augmentation rates for all countries, is rejected. The hypothesis of identical augmentation rate parameters for labor is not tested, given that the hypothesis of zero output and labor augmentation rates is not rejected.

The Structure of Technology

Finally, we explore the structure of the technology as represented by the meta-production function. The hypotheses of interest are whether the production function is Cobb-Douglas, that is,

$$B_{kk} = B_{11} = B_{k1} = 0 \;;$$

and whether the production function is generalized Cobb-Douglas, that is:

$$B_{kk} = a_k/a_1 \; B_{k1} \quad ; \quad B_{11} = a_1/a_k \; B_{k1} \; .$$

We assign a level of significance of 0.01 to this series of tests, to be allocated equally between the Cobb-Douglas and generalized Cobb-Douglas hypotheses. Both hypotheses, conditional on the maintained hypotheses of the study, are rejected. The results of tests of European communality and the structure of technology are presented in Table 5.3.

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[11] In fact, the hypotheses cannot be rejected for all countries in the sample.

6. Empirical Results--Estimates of Parameters

We synthesize the results of the hypothesis testing of the last section and impose the restrictions implied by the hypotheses that are not rejected at the chosen levels of significance. The results are presented in the first column of Table 6.1. The estimated capital augmentation rates are statistically significant and positive for all countries. West Germany has the highest rate--15.7 percent per annum and the United States has the lowest rate--8.2 percent per annum. As mentioned previously, the estimates of augmentation level and rate parameters should be interpreted carefully. For example, an increase in computer literacy may be reflected as an augmentation of capital (an increase in the effective number of computers).

We further note that the estimated capital augmentation rates for France, West Germany and Japan are very similar. This similarity is consistent with the hypothesis of convergence of technology among these industrialized countries. We test and cannot reject the hypothesis that the capital augmentation rates of the three countries are identical (the value of χ^2 divided by the degrees of freedom is 2.94). We thus impose the restrictions implied by the hypothesis of convergence for these countries on the estimation and report the results in the second column of Table 6.1. (Recall, however, that the hypotheses of identical capital augmentation rates for all or European countries have been rejected.) The estimates in the two columns do not differ appreciably.

Functions of Parameters of Interest

In Table 6.2 we compute some parameters of the aggregate production function of interest for the different countries in 1970. We note that our estimates of capital elasticities are lower than those estimated from the more conventional factor share method under the assumptions of constant returns to scale and profit maximization with competitive markets. Our estimates of the labor elasticities are comparable to the actual shares of labor costs in total output for France, West Germany, and Japan and somewhat lower for the United Kingdom and the United States. This finding suggests that labor may possibly be paid more than its marginal product in both the U.K. and the U.S. But capital is probably also paid more than its marginal product in all five countries because there are decreasing returns to scale and capital is the residual claimant to output.

We have previously rejected the hypotheses of homogeneity and constant returns to scale in production. This implies that the degree of returns to scale not only is not unity but also depends on the quantities of capital and labor. At the 1970 values of the independent variables of each country, statistically significant decreasing returns to scale are exhibited for all countries.[12] The estimated degrees of returns to scale range between 0.7 and 0.75. This finding may possibly be attributed to omitted factors of production such as land, public capital stock (in the case of Japan and the United States), human capital, R&D capital stock, and the environment.

The degree of local returns to scale for the ith country may be computed as:

$$(6.1)\quad \mu_i(K,L,t) = \frac{\partial \ln F}{\partial \ln \lambda}(\lambda e^{c_{iK}t}K, \lambda L)\Big|_{\lambda=1}$$

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[12]The t-ratios for the null hypothesis that the degree of returns to scale is equal to unity, that is, the null hypothesis of constant returns to scale, are 3.283 for France, 3.998 for West Germany, 3.037 for Japan, 3.763 for the United Kingdom and 2.427 for the United States.

$$= a_k + a_l + (B_{kk}+B_{kl}) \ln K + (B_{kl}+B_{ll}) \ln L$$

$$+ (B_{kk}+B_{kl})c_{iK}t$$

$$= 0.645 + 0.004 \ln K + 0.034 \ln L$$

$$+ 0.004 c_{iK}t.$$

What this equation says is that the degree of local returns to scale increases with the quantities of capital and labor, and time, particularly with respect to labor. However, for the period under study, the degree of local returns to scale is significantly less than unity, that is, returns to scale are sharply decreasing.

The rate of local technical progress realized may be computed as:

$$(6.2) \qquad \tau_i(K,L,t) = \frac{\partial \ln F}{\partial t}(e^{c_{iK}t}K,L)$$

$$= \frac{\partial \ln F}{\partial \ln K}(e^{c_{iK}t}K,L)c_{iK}$$

$$= (a_k + B_{kk} \ln K + B_{kl} \ln L + B_{kk}c_{iK}t) \cdot c_{iK}$$

$$= (0.132 - 0.039 \ln K + 0.043 \ln L - 0.039 c_{iK}t)c_{iK} .$$

What this equation says is that the rate of local technical progress, given the rate of capital augmentation, declines with the level of capital and time but rises with the level of labor. Thus, even though the rates of capital augmentation are exogenously determined, the rate of technical progress realized depends on the quantities of capital and labor and to that extent may be regarded as endogenous.

The degrees of local returns to scale and the rates of local technical progress are plotted against time for each country in Figure 6.1 and Figure 6.2 respectively. It is interesting to note that locally, for every country, the degree of returns to scale is less than unity but rising over time. By contrast, the rate of technical progress declines with time. In fact, the rates of local technical progress show strong signs of convergence, over time, despite significant differences in the rates of growth of the inputs and in the rates of capital augmentation across countries. This decline in the rate of local technical progress may be largely attributed to the diminishing marginal productivity of capital due to increases in both capital and in time. However, the convergence in the local rates of technical progress realized, which depend on the quantities of inputs as well as time, should be carefully distinguished from the convergence in the rates of capital augmentation, which are assumed fixed and exogenous in this study. Both types of convergence must be further distinguished from the convergence of levels or rates of growth of real output or real output per capita.

Finally, we compute and plot the estimated marginal productivity of capital against time for each country in Figure 6.3. Figure 6.3 shows that Japan had an extremely high marginal productivity of capital in the 1950's and 1960's. However, it declined continuously until it reached the same level as the United States on the 1980's. (Could this have partially explained the large capital flows between Japan and the United States in the 1980's?). The marginal productivity of capital of the United States, gross of depreciation, was relatively stable throughout the period at 20 percent. Assuming an average rate of depreciation of capital (equipment and structures) of 10 percent per annum, this implies a real (before tax) rate of return to capital of approximately 10 percent.[13] By comparison, the marginal productivities of capital of France, West Germany and United Kingdom drifted lower (to less than 10 percent) but appeared to converge together.[14] (Could this be due to increased capital mobility within Europe?).

Is Technical Progress Capital-Saving or Labor-Saving?

One interesting question is whether capital-augmenting technical progress is also capital saving, in the sense that the (cost-minimizing) demand for capital relative to labor,[15] at given quantity of output and prices of capital and labor, is reduced as a result of the technical progress. In Appendix 1, it is shown that capital-augmenting technical progress is capital-saving if and only if the elasticity of substitution between capital and labor is less than unity in absolute value. In Table 6.3, we present estimates of $\frac{\partial \ln (K/L)}{\partial \ln A_K(t)}$, which are all negative, indicating that technical progress has been capital-saving rather than labor-saving in all of the countries. One implication of the capital-saving nature of technical progress is that structural unemployment for the aggregate economy

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[13]Recall the well-known formula for the real "user cost of capital" under the assumption of constant exponential depreciation:

$\frac{\partial F}{\partial K} = r + \delta$, where r is the real rate of interest and δ the rate of depreciation. See Arrow (1964).

[14]The lower levels of the marginal productivities of these countries may be partially attributed to the difference in their definitions of measured capital stocks.

[15]Recall that the hypothesis of profit maximization has been rejected.

is unlikely to be technologically induced. Instead, new technology makes a given quantity of capital go further as a complementary input to labor.

In the last column of Table 6.3, the estimated elasticities of substitution of the five countries at the 1970 values of capital and labor are presented. They are all less than 0.5 in absolute value, suggesting relatively low substitutibility between capital and labor.

Monotonicity and Concavity

Also presented in Table 6.3 are the estimates of the values of the elements of the gradient and the Hessian matrix of the production function for the five countries in 1970. The first partial derivatives are all positive. The own second-partial derivatives are all negative and the determinants of the Hessian matrices are all positive. Thus the estimated translog production function is monotonically increasing and concave at least within a convex neighborhood of the 1970 values of the independent variables.

Purchasing Power Parity Adjustment

We have not made explicit purchasing-power-parity (PPP) adjustments on the data. Several considerations are relevant. First, given our assumption of a country-specific, commodity-augmentation form of technical progress, merely substituting the PPP exchange rates for the market exchange rates in 1980 in the conversion of the investment and GDP data from constant local currency to constant U.S. dollars has <u>no</u> effect on our results <u>except</u> the estimates of the augmentation <u>level</u> parameters. Thus, a serious effort at PPP adjustment requires separate adjustment factors for real output and for real investment for each of the countries for each year of the sample period. Second, to the extent that such adjustments are (separately for real output and capital) either approximately proportional or trended across countries, they would also have already been reflected in the country- and commodity-specific time-varying augmentation factors. Third, there is one theory of purchasing power parity which says that the true gap in the real output between two countries is overstated by the market exchange rates;[16] in fact,

$$\ell n\ Y^{**}_{it} = \delta_i\ \ell n\ Y_{it} \tag{6.3}$$

where Y^{**}_{it} is the "true" real output of the ith country at time t and Y_{it} is the measured real output of the ith country at time t, converted at the market exchange rates. Equation (6.3) implies that the second-order parameters of the translog production function in terms of the measured output and inputs are proportional to, but not identical with, one another across countries. If and only if $\delta_i = \delta$, $\forall$ i, are the second-order parameters identical. However, since the hypothesis of a single meta-production function with identical second-order parameters across countries cannot be rejected, we conclude that the differences among the δ_i's, if any, are not statistically significant and a PPP adjustment is not likely to alter the qualitative nature of our results.

7. Growth Accounting

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[16] See, e.g., David (1972).

One application of the estimated production function parameters is to use them to compute alternative estimates of the rate of technical progress, without relying on the assumptions of constant returns to scale, neutral technical progress and profit maximization. In Table 7.1, we present a summary of the data on the five countries over the sample periods. The data show that Japan had the highest average annual rate of growth of real GDP and the United Kingdom the lowest. Japan also had the highest average annual rate of growth of capital stock and U.K. the lowest. The United States had the highest rate of growth of the labor force and West Germany the lowest. In Table 7.2, we compare our estimates of the average annual rates of technical progress (or equivalently rates of growth of total factor productivity) with estimates obtained using the conventional method.

Our estimates of the average annual rates of technical progress are calculated as follows. Let $\ell n\hat{F}(\cdot)$ be the estimated translog production function. Let $t = 0$ be the initial period and $t = T$ be the terminal period. Recall that technical progress is the rate of growth of output, holding inputs constant. Thus, the average annual rate of technical progress may be estimated as:

$$\text{(7.1)} \qquad \lambda_0 = \frac{1}{T}\left[\ell n\ \hat{F}(K_0, L_0, T) - \ell n\ \hat{F}(K_0, L_0, 0)\right]$$

where K_0 and L_0 are the quantities of capital and labor in the initial period. It may also be estimated as:

$$\text{(7.2)} \qquad \lambda_T = \frac{1}{T}\left[\ell n\ \hat{F}(K_T, L_T, T) - \ell n\ \hat{F}(K_T, L_T, 0)\right]$$

where K_T and L_T are the quantities of capital and labor in the terminal period. The two estimates λ_0 and λ_T will in general not coincide unless technical progress is neutral. In this study, the average annual rate of technical progress is estimated as the average of λ_0 and λ_T:

$$(7.3) \qquad \lambda = (\lambda_0 + \lambda_T)/2.$$

The conventional estimates of the average annual rates of technical progress are calculated as follows. Let

$$(7.4) \qquad s_{it} = w_{it}L_{it}/p_{it}Y_{it}$$

be the share of labor costs in the GDP of the ith country at time t. Then the rate of technical progress between period t and period t-1 may be estimated by the Tornqvist index number:[17]

$$\begin{aligned}(7.5) \qquad \lambda_{it} = {} & \ell n\, Y_{it} - \ell n\, Y_{i(t-1)} \\ & - (1-(s_{it}+s_{i(t-1)})/2)(\ell n\, K_{it} - \ell n\, K_{i(t-1)}) \\ & - ((s_{it}+s_{i(t-1)})/2)(\ell n\, L_{it} - \ell n\, L_{i(t-1)}) .\end{aligned}$$

The validity of equation (7.5) depends on the assumptions of constant returns to scale and profit maximization with competitive markets. The average annual rate of technical progress between period 0 and period T may be estimated, under the assumption of neutrality, by:

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[17] See, e.g., Jorgenson, Gollop and Fraumeni (1987) for an exposition of the use of this index number in the measurement of technical progress.

$$(7.6) \qquad \lambda_i^* = (\sum_{t=1}^{T} \lambda_{it})/T$$

$$= (\ell n\, Y_{iT} - \ell n\, Y_{i0})/T$$

$$- \sum_{t=1}^{T} (1 - (s_{it}+s_{i(t-1)})/2)\ (\ell n\, K_{it} - \ell n\, K_{i(t-1)})/T$$

$$- \sum_{t=1}^{T} (s_{it}+s_{i(t-1)})/2 \cdot (\ell n\, L_{it} - \ell n\, L_{i(t-1)})/T \ .$$

Moreover, the second and third terms on the right-hand side of equation (7.6) may be interpreted as the contributions due to the growth of capital and labor respectively.

We note significant differences between the two alternative sets of estimates of technical progress in Table 7.2. Our estimates are much higher, partially reflecting our finding of a lower capital elasticity and hence decreasing returns to scale for the five countries, and show much greater dispersion. The rankings of the countries by the rate of (realized) technical progress also change significantly, with, for example, Japan moving from last place to first place and the United Kingdom from third place to last place.

In Table 7.3, we present two alternative sets of estimates of the relative contributions of the different sources of growth for each of the five countries, first using our estimated aggregate production functions and secondly using the conventional approach. Our estimates of the average annual contributions of capital are calculated as follows. First, we have, for an estimate of the average annual contribution of capital, (7.7) $$C_{K0} = \frac{1}{T} \; [\ell n \; \hat{F}(K_T, L_0, 0) - \ell n \; \hat{F}(K_0, L_0, 0)], \text{ or}$$

(7.8) $$C_{KT} = \frac{1}{T} \; [\ell n \; \hat{F}(K_T, L_T, T) - \ell n \; \hat{F}(K_0, L_T, T)].$$

As in the case of technical progress, the average annual contribution due to capital is taken to be the average of C_{K0} and C_{KT}. The average annual contribution due to labor can be similarly estimated.

We find that over the period under study, technical progress is the most important source of economic growth, accounting for more than 50 percent (more than 80 percent for the European countries), and capital is the second most important source of economic growth (except, by 1 percent, for the U.S.). Labor accounts for less than 5 percent except for the United States. These results may be contrasted to those of the conventional approach which identify capital as the most important source of economic growth (more than 40 percent), followed by technical progress (between 15 and 52 percent). By either approach, capital and technical progress combined account for more than 95 percent of the economic growth of France, West Germany, Japan and the United Kingdom. In the United States, where the labor force grew more rapidly than in other countries during this period, they still account for 75 percent of the economic growth.

The reason why the combined contributions of capital and technical progress are similar by either approach is because the contributions of labor are very similar by either approach--our estimated output elasticities with respect to labor are not that different from those obtained by the factor share method. However, our approach yields much lower output elasticities with respect to capital than those obtained by the factor share method under the constant returns to scale assumption. Thus, our estimated contributions of the remaining factor, technical progress, must be correspondingly higher. Another way of understanding our results is to observe that our low estimated capital elasticities lead to decreasing rather than constant returns to scale and thus the estimated rates of technical progress must be higher to be consistent with the same rates of growth of real output and inputs.

We should emphasize, however, the complementary nature of capital and technical progress. A growth decomposition exercise is essentially a first-order one and cannot take the complementarity into account. Given our finding that technical progress is capital-augmenting, capital and technology are inextricably intertwined and are both indispensable ingredients for economic growth.

Finally, we plot our estimates of the rates of capital augmentation against the rates of growth of capital for the different countries in Figure 7.1. It is apparent that there is a positive, but non-linear, relationship between the rate of capital augmentation (Solow-neutral technical progress) and the rate of growth of capital. However, there also appears to be an asymptote to the capital augmentation rate so that, beyond a certain point, increases in the rate of growth of capital have no effect on the rate of capital augmentation. One conjecture that is consistent with the scatter-diagram in Figure 7.1 is that at any given time there is only so much new technology ready for immediate exploitation--once this is exhausted, further increases in investment have little effect in raising the current technological level even though they may raise real output.

8. International and Intertemporal Comparison

A second application of the estimated production function parameters is to compare the evolution of the productivities of the different countries over time. In Figure 8.1, we plot the real output per labor-hour of each of the five countries against time. The United States had the highest real output per labor-hour until it was overtaken by France and West Germany in the mid-1970's. The United Kingdom fell behind France and West Germany in the late 1950's. Japan started in the last place at a very low level but by 1985 had narrowed the gap considerably. However, real output per labor-hour may differ across countries because of differences in capital intensity (capital stock per unit labor) and scale, as well as in efficiency and technical progress. In Figure 8.2, we plot the quantity of the real capital stock per worker in the labor force of each of the five countries, adjusted for coverage, against time.[18] We note that the U.S. had the highest level of capital stock per worker until around 1970, when it was overtaken by the European countries, due in part to the higher rate of growth of the labor force in the United States. However, the measured capital stock per worker of the United States was still significantly higher than that of Japan as of 1985 even though the rate of growth of the Japanese capital stock was three times that of the United States. As of 1985, West Germany had the highest measured capital stock per worker, followed by France and the U.K.

In Figure 8.3 we plot the quantity of real output per unit of the measured capital stock of each of the five countries, again adjusted for coverage, against time. We note that capital productivity showed a

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[18]In Figure 8.2, the capital stock data include only private non-residential capital.

generally declining trend except for the United States where it was approximately constant. What this implies is that the capital-output ratio, the reciprocal of capital productivity, must have been rising over time, except for the United States.

Figures 8.1, 8.2 and 8.3 are all based on the conversion from constant local currency units into constant U.S. dollars by the market exchange rates prevailing in 1980. In Appendix 3, we assess the effect of using the "purchasing-power-parity" exchange rates of Summers and Heston (1988) on the relative levels of real output per labor-hour across the five countries.

In order to compare productive efficiencies across countries, we must net out the effects of capital intensity and scale. We note that within our framework, in terms of "efficiency"-equivalent quantities of output and inputs, the production functions of the different countries are, by definition, identical. In terms of the measured quantities of output and inputs, however, they are not identical. We therefore pose the hypothetical question: if all countries have the same quantities of measured inputs of capital and labor as the United States, what would have been the quantities of their real outputs and how would they evolve over time? In other words, we compare their productive efficiencies holding inputs constant.

To answer this question we project the time-series of hypothetical real outputs for each country by the formula:

$$(8.1) \quad \ell n\, Y_{it} = \ell n\, Y_0 - \ell n\, A_{i0} + a_k\, \ell n\, K_{USt} + a_l\, \ell n\, L_{USt} + B_{kk}(\ell n\, K_{USt})^2/2 + B_{ll}(\ell n\, L_{USt})^2/2 + B_{kl}(\ell n\, K_{USt})(\ell n\, L_{USt}) + (a_k c_{iK})t$$

$$+ (B_{kk}c_{iK})(\ell n\ K_{USt})t + (B_{kl}c_{iK})(\ell n\ L_{USt})t$$
$$+ (B_{kk}(c_{iK})^2)t^2/2\ ,$$

substituting in the estimated values of the parameters (Recall that the hypotheses of equal augmentation levels for capital and labor cannot be rejected). In order to implement equation (8.1), we need to estimate $\ell n\ Y_0$ and $-\ell n\ A_{i0}$ for all of the countries except the United States. However, by estimating the aggregate production function in the first-differenced form, $\ell n\ Y_0$ and the $-\ell n\ A_{i0}$'s are not directly estimated. It is therefore necessary to compute the implied estimates of $\ell n\ Y_0$ and the $-\ell n\ A_{i0}$'s by the formulae:

$$(8.2)\quad \ell n\, \hat{Y}_0 = \Bigg[\sum_{t=0}^{T} \ell n\, Y_{USt} - \hat{a}_k \sum_{t=0}^{T} \ell n\, K_{USt} - \hat{a}_l \sum_{t=0}^{T} \ell n\, L_{USt}$$

$$- \hat{B}_{kk} \sum_{t=0}^{T} (\ell n\, K_{USt})^2/2 - \hat{B}_{ll} \sum_{t=0}^{T} (\ell n\, L_{USt})^2/2$$

$$- \hat{B}_{kl} \sum_{t=0}^{T} (\ell n\, K_{USt})(\ell n\, L_{USt})$$

$$- \hat{a}_k \hat{c}_{USK} \sum_{t=0}^{T} t$$

$$- \hat{B}_{kk} \hat{c}_{USK} \sum_{t=0}^{T} (\ell n\, K_{USt})t - \hat{B}_{kl} \hat{c}_{USK} \sum_{t=0}^{T} (\ell n\, L_{USt})t$$

$$- (\hat{B}_{kk}(\hat{c}_{USK})^2) \sum_{t=0}^{T} t^2/2 \Bigg] /(T+1);$$

$$(8.3)\quad - \ell n\, \hat{A}_{i0} = \Bigg[\sum_{t=0}^{T} \ell n\, Y_{it} - (T+1)\ell n\, \hat{Y}_0$$

$$- \hat{a}_k \sum_{t=0}^{T} \ell n\, K_{it} - \hat{a}_l \sum_{t=0}^{T} \ell n\, L_{it}$$

$$- \hat{B}_{kk} \sum_{t=0}^{T} (\ell n\, K_{it})^2/2 - \hat{B}_{ll} \sum_{t=0}^{T} (\ell n\, L_{it})^2/2$$

$$- \hat{B}_{kl} \sum_{t=0}^{T} (\ell n\, K_{it})(\ell n\, L_{it})$$

$$- (\hat{a}_k \hat{c}_{iK}) \sum_{t=0}^{T} t$$

$$- \hat{B}_{kk} \hat{c}_{iK} \sum_{t=0}^{T} (\ell n\, K_{it})t - \hat{B}_{kl} \hat{c}_{iK} \sum_{t=0}^{T} (\ell n\, L_{it})t$$

$$- (\hat{B}_{kk}(\hat{c}_{iK})^2) \sum_{t=0}^{T} t^2/2 \Bigg] /(T+1).$$

The implied estimates of $-\ell n\ \hat{A}_{i0}$'s are presented in Table 8.1. The $-\ell n\ \hat{A}_{i0}$'s reflect the output augmentation levels (or efficiencies) of the different countries relative to the United States in the base year, as well as possible differences in definitions and measurements of the variables. We find that in the base year (1970), the United States had the highest output efficiency, followed by France, West Germany, Japan and the United Kingdom, in that order. France, West Germany and Japan were actually very close to one another--all of them had an output efficiency of approximately 60 percent of the United States. The United Kingdom had an output efficiency of slightly more than 40 percent of the United States.

Similarly, the implied estimates of a_{1i}^{**}'s can be computed from the labor share equation, given the estimated values of the parameters from the first-differenced form. The results are presented in Table 8.2, along with the directly estimated values of the a_{1i}^{*}'s from the aggregate production function, which turn out to be identical for all countries. Under the hypothesis of competitive profit maximization with respect to labor, $a_{1i}^{*} = a_{1i}^{**}$, $\forall$ i. A comparison of the two sets of estimates therefore provides additional information on the validity of the hypothesis. Unfortunately, they turn out to be quite different, further undercutting the validity of the hypothesis of profit maximization.

In Figures 8.4 through 8.8 we compare the time-series of the real outputs predicted for each of the five countries from our model using the estimates of the parameters in column 1 of Table 6.1 with that of the actual real outputs. This provides an indication of the goodness of fit of the model of capital-augmenting technical progress. Overall, the model seems to fit quite well.

Given the estimated values of $\ell n\ \hat{Y}_0$, $-\ell n\ \hat{A}_{i0}$'s and the parameters of the aggregate production function, equation (8.1) is used to project the level of real output that would have been produced by each country in each period if it had the measured inputs of the United States in that period. The results are plotted for each country in Figure 8.9.

Figure 8.9 shows that in 1949 the United States had the highest level of overall productive efficiency, the United Kingdom the second highest (but considerably lower than the United States), and West Germany the lowest. By the mid-1950's France, West Germany and Japan had overtaken the United Kingdom. As of 1985, the United States remained in the first place and the United Kingdom in last place, with France, West Germany and Japan closely clustered together. Starting at less than 40 percent of the productive efficiency of the United States in 1949, the latter three countries had reached approximately two-thirds of the productive efficiency of the U.S. by 1985. The gap between the United Kingdom and the United States only narrowed very slightly during this period.

In Figure 8.10 we plot the relative productive efficiency of each of the four countries against time, using the United States level as the reference (that is, with U.S. productive efficiency normalized at unity). Figure 8.10 provides the same picture as Figure 8.9, namely, that France, West Germany and Japan have closed the gap significantly but not the United Kingdom. The two interesting questions that emerge are: What accounts for the initial and still considerable U.S. edge (size, land input, natural resources, greater degree of economic competition, economic and social mobility, etc.)? And why is the U.S. losing ground to France, West Germany and Japan (declining educational standards, falling ratio of public to private investment)?[19] These questions await further study.

One natural definition of convergence across countries is based on their production technologies. Two countries are said to have converged to each other, if, given the same inputs, they produce approximately the same output. Based on this definition of convergence, the country with the lower level of productive efficiency should have a higher rate of technical progress (or equivalently growth of total factor productivity). Figure 8.10, which shows the differences in productive efficiency narrowing among nations over time, provides empirical evidence in support of this hypothesis of convergence.

9. Conclusion

We have presented a new analysis of the characteristics of post-war economic growth, such as the rates and patterns of technical progress and scale economies, using pooled time series data from the Group-of-Five countries. We have found that the empirical data are inconsistent with the hypothesis of constant returns to scale, at the aggregate, national level. In fact, there are sharply decreasing local returns to scale. Moreover, we have found that technical progress is non-neutral. In fact, it is capital-augmenting.[20] We have also found that the empirical data are inconsistent with the hypothesis of profit maximization with respect to labor under

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[19] In the context of the framework here, this is equivalent to asking why the augmentation rate for capital is so much lower in the United States compared to France, West Germany and Japan.

[20] David and van de Klundert (1965) have also found non-neutral technical progress in their study but with a bias that is opposite in direction to what is found here.

competitive conditions. All of these hypotheses are, however, necessary for the validity of the conventional method of measuring the rate of growth of total factor productivity and of growth accounting.

Based on our new approach, we have obtained alternative estimates of the rates of growth of total factor productivity as well as alternative decompositions of economic growth into its sources--capital, labor and technical progress--that are independent of the conventional assumptions. We have found much higher and more dispersed rates of realized technical progress. We have also found that technical progress is by far the most important source of economic growth of the industrialized countries in our sample, accounting for more than 50 percent.

What are the implications of capital-augmenting technical progress? It implies that the aggregate production function can be written in the form:

$$(9.1) \qquad Y = F(A(t)K, L).$$

Thus, the benefits of technical progress are higher the higher the level of the capital stock. A country with a low level of capital stock relative to labor will not benefit as much from technical progress as a country with a high level of capital relative to labor. Capital and technical progress are, in a word, complementary. Moreover, capital-augmenting technical progress implies that the rate of realized technical progress, defined as the growth in real output holding inputs constant,

$$(9.2) \qquad \frac{\partial \ell n\ Y}{\partial t} = \frac{\partial \ell n\ F}{\partial \ell n\ K}(A(t)K,L) \cdot \frac{\dot{A}(t)}{A(t)},$$

depends on the elasticity of output with respect to measured capital as well as the rate of capital augmentation. The former in turn depends on the actual quantities of capital and labor. In our model, the rate of capital augmentation, $\dot{A}(t)/A(t)$, is taken to be exogenous and equal to a constant for each country, but the rate of realized technical progress, $\frac{\partial \ell n Y}{\partial t}$, which varies with the quantities of capital, labor and time, through the elasticity of output with respect to capital, is endogenous.

The consequence of this capital-technology complementarity can be readily appreciated from our empirical results. Consider France, West Germany and Japan. They all have almost the <u>same</u> estimated rate of capital augmentation of between 14 and 16 percent <u>per annum</u>. However, according to our estimates in Table 7.2, Japan has the highest average annual rate of (realized) technical progress, followed by France and then West Germany, in the same order as their respective rates of growth of capital stock (See Table 7.1). This is precisely the complementarity of capital and technical progress at work.

However, we should emphasize that a zero rate of labor augmentation does not necessarily mean that the quality of labor has not improved over time, or that all the investments in human capital have gone to waste. As mentioned earlier, improvements in the quality of labor may manifest themselves in the form of capital-augmenting technical progress.

At the aggregate level, one implication of capital-augmenting technical progress is the importance of capital to long-term economic growth. The benefits of technical progress to the economy are directly proportional to the size of the capital stock. An increase in the saving rate which results in a higher level of capital formation may also bring about an acceleration in the rate of economic growth in the short and intermediate runs. A second implication, given that the elasticity of substitution between capital and labor has been found to be less than unity, is that technical progress is capital-saving rather than labor-saving, in the sense that the desired capital-labor ratio for given prices of capital and labor and quantity of output declines with technical progress (See Appendices 2 and 3). Capital-augmenting technical progress is thus less likely to cause structural unemployment through the technological displacement of workers. In fact, given that F_{KL}, the cross-partial derivative of output with respect to capital and labor, is positive (see Table 6.3), capital-augmenting technical progress is likely to enhance employment, in the intermediate and long runs.

Capital-augmenting technical progress also has implications for optimal investment, depending on whether technical progress is anticipated or not and how its benefits and costs are allocated.

The results of our growth accounting exercise identify technical progress as the most important source of economic growth. While this finding may be reminiscent of the findings of a large unexplained "residual" in early studies of economic growth, they are, in fact, quite different on at least two counts. First, the early studies typically assume constant returns to scale, neutrality of technical progress, and profit maximization with competitive markets. Second, while technical progress is, in the form of capital augmentation, assumed to be exogenous in our model, as in the early studies, we have found it to be complementary to capital so that it does a country with a low level of capital stock much less good than a country with a high level. This capital-technology complementarity, which implies a positive interactive effect of capital and technical progress, distinguishes our results from others.

Thus, it would be wrong to interpret our finding to mean that capital is not an important source of economic growth. In addition to its direct contribution, capital also enhances the effect of technical progress on economic growth.

Technical progress (specifically the rates of commodity augmentation) is taken as exogenous in this study. Moreover, the rates of augmentation are assumed to be constant over time. It is, however, remarkable that the rates of augmentation of capital turn out to be almost identical for France, West Germany and Japan--the hypothesis of convergence among these countries cannot be rejected--indicating that the three countries have nearly the same access to advances in technology. It will be of interest to explore why the convergence hypothesis does not seem to apply to the U.K. and the U.S. and more generally to investigate the determinants of the observed variations in the rate and pattern of technical progress (can it be satisfactorily explained by capital accumulation, education, R&D expenditures, the ratio of public to private investment, or other factors?). It will also be interesting to allow the possibility of augmentation rates that vary over time. We have already seen some evidence that the rates of capital augmentation appear to be related to the rates of growth of capital (Figure 7.1). It may well be the case that they are related to the rates of growth of human capital as well.

We have also not made explicit adjustments for the quality of capital or labor, as were done by Jorgenson, Gollop and Fraumeni (1987). Instead, we allow any trend of improving input quality to be captured by the rates of capital and labor augmentation themselves. Thus, what we attribute to technical progress include what others may attribute to the improvement in the qualities of the inputs.

Our findings also indicate that the rate of growth of real output is lower in the United States than in Japan not only because of the lower rate of growth of the capital input (capital accumulation), but also because of a lower rate of capital augmentation (8 percent for the United States compared with 14 percent for Japan). This lower rate of capital augmentation may reflect increasing constraints in the efficient utilization of capital in the United States. Among the factors commonly put forward to explain the low efficiency of capital are: the deteriorating capital infrastructure, declining educational standards, increasing problems in the natural and legal environments, rising "agency costs" and generally declining "social capability".[21] However, this also suggests that the United States economy is operating well within the meta-production possibilities frontier and has the potential of achieving significant increases in real output through improvements in the efficiency, or the rate of augmentation, of capital without increases in the physical inputs. Whether and how this can be achieved are open questions.

Much additional work remains. Other promising future extensions of this research include: accounting for omitted factors such as land (see Lau and Yotopoulos (1989)), human capital, public capital (see Boskin, Robinson and Huber (1989)), R & D and environmental capital; allowing for vintage effects and for embodied technical progress; explaining (or endogenizing) the differences in the rates of commodity augmentation; as well as other

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[21]This terms was coined by M. Abramovitz.

statistical extensions.[22]

[22]For example, the variances of the stochastic disturbances may be different across countries; moreover, the stochastic disturbances may be contemporaneously correlated across countries because of joint shocks (such as the oil shocks).

Appendix 1

When Is Capital-Augmenting Technical Progress Also Capital-Saving?

We begin with a definition of capital-saving technical progress. Technical progress is said to be capital-saving if the demand for capital relative to labor, at given prices of capital and labor and given quantity of output, is reduced as a result of technical progress. Under capital-augmenting technical progress, the production function takes the form:

$$Y = F(A(t)K, L) \tag{A.1.1}$$

The cost function corresponding to such a production function, assuming competitive factor markets, is given by:

$$\begin{aligned} & C(r, w, t;\ Y) \\ & = \min_{K,L} \{rK + wL \mid F(A(t)K, L) \geq Y\} \\ & = \min_{K^*,L} \{r/A(t)K^* + wL \mid F(K^*, L) \geq Y\} \\ & = C(r/A(t), w;\ Y) \end{aligned} \tag{A.1.2}$$

where r and w are the prices of capital and labor respectively.

By Shephard's (1953) Lemma, the demand for capital is given by:

$$\begin{aligned} K & = \frac{\partial C}{\partial r}(r/A(t), w;\ Y) \\ & = \frac{1}{A(t)} C_r(r/A(t), w;\ Y). \end{aligned} \tag{A.1.3}$$

The own-price derivative of K is given by:

(A.1.4) $$\frac{\partial K}{\partial r} = C_{rr}(r/A(t),w;\ Y)/A(t)^2 \ .$$

The demand for labor is given by:

(A.1.5) $$L = \frac{\partial C}{\partial w}\,(r/A(t),w;\ Y) = C_w \ .$$

The cross-price derivative of L is given by:

(A.1.6) $$\frac{\partial L}{\partial r} = C_{wr}/A(t)$$

The effect of capital-augmenting technical progress on the demand for capital <u>relative</u> to labor is given by:

$$\begin{aligned}
\frac{\partial K/L}{\partial A(t)} &= \frac{\partial}{\partial A(t)}\left[\frac{C_r/A(t)}{C_w}\right] \\
&= -\frac{1}{A(t)^2}\,C_r/C_w - \frac{1}{A(t)^3}\,\frac{C_{rr}r}{C_w} \\
&\quad + \frac{C_r/A(t)}{C_w^2}\,\frac{C_{wr}r}{A(t)^2} \\
&= \frac{C_r/A(t)}{C_w}\cdot\left(\frac{-1}{A(t)}\right)\left[1 + \frac{C_{rr}r/A(t)}{C_r} - \frac{C_{wr}}{C_w}\,r/A(t)\right] \\
&= -\frac{K}{L}\,\frac{1}{A(t)}\left[1 + \frac{\partial \ln K}{\partial \ln r} - \frac{\partial \ln L}{\partial \ln r}\right] .
\end{aligned}$$

However, by symmetry,

$$\frac{\partial L}{\partial r} = \frac{\partial K}{\partial w}$$

so that:

$$\frac{\partial \ \ell n \ L}{\partial \ \ell n \ r} = \frac{r}{L}\frac{\partial L}{\partial r} = \frac{r}{L}\frac{\partial K}{\partial w}$$

$$= \frac{rK}{wL}\frac{\partial \ \ell n \ K}{\partial \ \ell n \ w} .$$

But $\frac{\partial \ \ell n \ K}{\partial \ \ell n \ r} + \frac{\partial \ \ell n \ K}{\partial \ \ell n \ w} = 0$ because of zero degree homogeneity of cost-minimizing demand functions, thus:

$$\frac{\partial \ \ell n(K/L)}{\partial \ \ell n \ A(t)} = - \left[1 + \frac{\partial \ \ell n \ K}{\partial \ \ell n \ r} \left(1 + \frac{rK}{wL} \right) \right]$$

(A.1.7) $$= - \left[1 + \frac{\partial \ \ell n \ K}{\partial \ \ell n \ r} \bigg/ \frac{wL}{C} \right]$$

Capital-augmenting technical progress is capital-saving if $\frac{\partial \ \ell n \ K}{\partial \ \ell n \ r}$ $\frac{wL}{C}$ is greater than -1, in other words, if the own-price elasticity of demand for capital is not too large. In practice, equation (A.1.7) can be used to determine whether technical progress is capital-saving, with rK/wL estimated by using the relationship

(A.1.8) $$rK/wL = \frac{\partial \ \ell n \ F}{\partial \ \ell n \ K} \bigg/ \frac{\partial \ \ell n \ F}{\partial \ \ell n \ L} ,$$

which is implied by the first-order conditions for cost minimization.

Finally, we note that $-\frac{\partial \ \ell n\ K}{\partial \ \ell n\ r}\left(1+\frac{rK}{wL}\right)$ may be recognized as the elasticity of substitution between capital and labor, so that as long as the elasticity is less than unity, technical progress is capital-saving.

Appendix 2

Calculation of the Own-Price Elasticity of the Demand for Capital

The first-order conditions for cost minimization (Recall that the hypothesis of profit maximization is rejected) under the assumption of capital-augmenting technical progress are:

(A2.1) $\lambda F_K(A(t)K,L) = r/A(t);$

(A2.2) $\lambda F_L(A(t)K,L) = w;$

(A2.3) $F(A(t)K,L) = \bar{Y}.$

where $Y = F(A(t)K,L)$ is the production function, $F_K(\cdot)$ and $F_L(\cdot)$ are the partial derivatives of the production function with respect to the first and second arguments respectively, λ is the Lagrange multiplier, and r and w are the prices of capital and labor respectively. Differentiating this system of three equations with respect to r, we obtain:

$$F_K A(t) \frac{\partial K}{\partial r} + F_L \frac{\partial L}{\partial r} = 0,$$

$$\lambda F_{KK} A(t) \frac{\partial K}{\partial r} + F_{KL} \frac{\partial L}{\partial r} + F_K \frac{\partial \lambda}{\partial r} = A(t) ,$$

$$\lambda F_{KL} A(t) \frac{\partial K}{\partial r} + \lambda F_{LL} \frac{\partial L}{\partial r} + \frac{\partial \lambda}{\partial r} = 0 .$$

This system of three equations can be rewritten as:

$$\text{(A2.4)} \quad \begin{bmatrix} 0 & F_K & F_L \\ F_K & F_{KK}A(t) & F_{KL} \\ F_L & F_{KL}A(t) & F_{LL} \end{bmatrix} \begin{bmatrix} \frac{\partial \ln \lambda}{\partial r} \\ \frac{\partial K}{\partial r} \\ \frac{\partial L}{\partial r} \end{bmatrix} = \begin{bmatrix} 0 \\ 1/A(t) \\ 0 \end{bmatrix}$$

For 1970, $A(t) = 1$, and $\frac{\partial K}{\partial r}$ can be calculated as:

$$\text{(A2.5)} \quad \frac{\partial K}{\partial r} = \frac{\begin{vmatrix} 0 & 0 & F_L \\ F_K & 1 & F_{KL} \\ F_L & 0 & F_{LL} \end{vmatrix}}{\begin{vmatrix} 0 & F_K & F_L \\ F_K & F_{KK} & F_{KL} \\ F_L & F_{KL} & F_{LL} \end{vmatrix}} = \frac{-F_L^2}{\begin{vmatrix} 0 & F_K & F_L \\ F_K & F_{KK} & F_{KL} \\ F_L & F_{KL} & F_{LL} \end{vmatrix}}$$

Now,

$$\text{(A2.6)} \quad F_{KK} = -\frac{Y}{K^2}\frac{\partial \ln F}{\partial \ln K} + \frac{Y}{K^2}\left(\frac{\partial \ln F}{\partial \ln K}\right)^2 + \frac{Y}{K^2}\frac{\partial^2 \ln F}{\partial \ln K^2}$$

$$\text{(A2.7)} \quad F_{KL} = \frac{Y}{KL}\frac{\partial^2 \ln F}{\partial \ln K\, \partial \ln L} + \frac{Y}{KL}\left[\frac{\partial \ln F}{\partial \ln K} \cdot \frac{\partial \ln F}{\partial \ln L}\right];$$

$$\text{(A2.8)} \quad F_{LL} = -\frac{Y}{L^2}\frac{\partial \ln F}{\partial \ln L} + \frac{Y}{L^2}\left(\frac{\partial \ln F}{\partial \ln L}\right)^2 + \frac{Y}{L^2}\frac{\partial^2 \ln F}{\partial \ln L^2}.$$

For the transcendental logarithmic production function,

$$F_{KK} = \frac{\hat{Y}}{K^2}\left[\frac{\partial \ell n F}{\partial \ell n K}\left(\frac{\partial \ell n F}{\partial \ell n K} - 1\right) + B_{kk}\right],$$

$$F_{KL} = \frac{\hat{Y}}{KL}\left[\frac{\partial \ell n F}{\partial \ell n K}\frac{\partial \ell n F}{\partial \ell n L} + B_{kl}\right],$$

(A2.9)
$$F_{LL} = \frac{\hat{Y}}{L^2}\left[\frac{\partial \ell n F}{\partial \ell n L}\left(\frac{\partial \ell n F}{\partial \ell n L} - 1\right) + B_{ll}\right].$$

By substituting the 1970 values of $\hat{Y}$, K, L, $\frac{\partial \ell n F}{\partial \ell n K}$, $\frac{\partial \ell n F}{\partial \ell n L}$ and the estimated values of the parameters, $\frac{\partial K}{\partial r}$ can be estimated from equation (A2.5). The elasticity can be estimated as $\frac{r}{K}\frac{\partial K}{\partial r}$ where r is given by:

(A2.10)
$$r = wF_K/F_L .$$

Appendix 3

The Effect of "Purchasing-Power-Parity" Exchange Rate Conversion

What is the impact on our findings if "purchasing-power-parity" exchange rates of Summers and Heston (1988) are used instead of the market exchange rates in 1980 for the conversion into constant (1980) U.S. dollars? As discussed in section 6, this will have no impact on our finding of capital-augmenting progress nor on the magnitudes of the estimated augmentation rates but may have an impact on $\ell n \hat{Y}_0$ and $\ell n \hat{A}_{i0}$'s.

In Table A3.1 the market exchange rates used in this study are compared with the purchasing-power-parity exchange rates of Summers and Heston (1988). It indicates that the countries whose real outputs per labor-hour will be sensitive to alternative exchange rates are France and West Germany--their real outputs will have to be scaled down by 20 percent. The net result is that as of 1985, the United States would still have the highest real output per labor-hour among the five countries and Japan would still have the lowest. (See Figure A3.1).

Table 5.1: Tests of Maintained Hypotheses of Measurements of Productivity

Tested Hypothesis	Maintained Hypothesis	Assigned Level of Significance	Number of Restrictions	Test Statistic χ^2/degrees of freedom
I. Single Meta-Production Function	Unrestricted	0.01	12	0.78
II. Commodity Augmentation	I	0.01	5	0.31
III. (1) Homogeneity	I+II	0.005	2	17.11
(2) Constant Returns to Scale	I+II	0.005	3	14.46
(3) Neutrality	I+II	0.005	10	3.96
(4) Profit Maximization	I+II	0.005	15	3.36

Table 5.2: Tests of Hypotheses on Augmentation Factors

Tested Hypothesis	Maintained Hypothesis	Assigned Level of Significance	Number of Restrictions	Test Statistic χ^2/degrees of freedom
IV. (1) Identical Capital Augmentation Levels	I+II	0.005	4	0.74
(2) Identical Labor Augmentation Levels	I+II	0.005	4	3.39
V. Two-Rate Hypothesis				
(1) Zero Output Augmentation Rates	I+II	0.01	5	1.88
(2) Zero Capital Augmentation Rates	I+II	0.01	5	0.52
(3) Zero Labor Augmentation Rates	I+II	0.01	5	2.34
VI. One-Rate Hypothesis	I+II			
(1) Zero Output and Capital Augmentation Rates	I+II	0.01	10	3.85
(2) Zero Output and Labor Augmentation Rates	I+II	0.01	10	1.45
(3) Zero Capital and Labor Augmentation Rates	I+II	0.01	10	3.96
VII. (1) Identical Output Augmentation Rates	I+II+VI(2)	0.003	4	N.A
(2) Identical Capital Augmentation Rates	I+II+VI(2)	0.003	4	5.14
(3) Identical Labor Augmentation Rates	I+II+VI(2)	0.003	4	N.A.

Table 5.3: Tests of Hypotheses on Augmentation Factors of European Countries

Tested Hypothesis	Maintained Hypothesis	Assigned Level of Significance	Number of Restrictions	Test Statistic χ^2/degrees of freedom
VIII. (1) Identical Capital Augmentation Levels for Europe	I+II	0.003	2	1.16
(2) Identical Labor Augmentation Levels for Europe	I+II	0.003	2	1.07
IX. (1) Identical Capital Augmentation Rates for Europe	I+II+VI(2)	0.003	2	6.98
(2) Identical Labor Augmentation Rates for Europe	I+II+VI(2)	0.003	2	N.A.
X. (1) Cobb-Douglas Production Function	I+II	0.005	3	51.25
(2) Generalized Cobb-Douglas Production function	I+II	0.005	2	68.87

Table 5.4: Critical Values of χ^2 Divided by Degrees of Freedom

Degrees of Freedom	Levels of Significance			
	0.05	0.01	0.005	0.001
1	3.84	6.64	7.88	10.83
2	3.00	4.61	5.30	6.91
3	2.61	3.78	4.28	5.42
4	2.37	3.32	3.72	4.62
5	2.21	3.02	3.35	4.10
10	1.83	2.32	2.52	2.96
12	1.75	2.18	2.36	2.74
15	1.67	2.04	2.19	2.51

Table 6.1

Estimated Parameters of the Aggregate Production Function and the Labor Share Equation (First-Differenced Form)

Parameter	With Non-identical Capital Augmentation Rates: Estimate	With Non-identical Capital Augmentation Rates: T-ratio	With Identical Capital Augmentation for France, W. Germany and Japan: Estimate	With Identical Capital Augmentation for France, W. Germany and Japan: T-Ratio
<u>Aggregate Production Function</u>				
a_k	0.132	3.276	0.135	3.552
a_l	0.513	1.837	0.507	1.822
B_{kk}	-0.039	-4.019	-0.036	-4.888
B_{ll}	-0.009	-0.066	-0.002	-0.015
B_{kl}	0.043	2.226	0.037	2.569
c_{FK}	0.152	5.624	0.159	6.157
c_{GK}	0.157	5.896	0.159	6.157
c_{JK}	0.144	4.209	0.159	6.157
c_{UKK}	0.097	5.008	0.101	5.267
c_{USK}	0.082	5.340	0.086	6.276
$\bar{R}^2$	0.815		0.816	
D.W.	2.026		2.021	
<u>Labor Share Equation</u>				
B_{klF}	-0.147	-2.130	-0.146	-2.123
B_{KlG}	-0.184	-1.904	-0.180	-1.869
B_{KlJ}	-0.068	-2.205	-0.066	-2.159
B_{klUK}	-0.151	-1.303	-0.150	-1.294
B_{KlUS}	-0.049	-0.848	-0.047	-0.821
B_{llF}	0.170	0.854	0.172	0.863
B_{llG}	0.312	2.053	0.307	2.028
B_{llJ}	-0.370	-3.818	-0.372	-3.843
B_{llUK}	0.267	2.294	0.267	2.292
B_{llUS}	0.142	0.877	0.141	0.872
B_{Flt}	0.010	2.667	0.010	2.673
B_{Glt}	0.012	2.358	0.012	2.343
B_{Jlt}	0.014	3.827	0.014	3.788
B_{UKlt}	0.004	0.994	0.004	0.983
B_{USlt}	0.001	0.324	0.001	0.305
$\bar{R}^2$	0.230		0.230	
D.W.	1.795		1.796	

Table 6.2

Estimated Parameters of the Aggregate Production Functions
(at 1970 Values of the Independent Variables)

	Capital Elasticity	Labor Elasticity	Degree of Local Returns to Scale	Rate of Local Tech. Progress	Actual Labor Share
France	0.216 (7.534)	0.481 (5.113)	0.697 (7.553)	0.033 (12.908)	0.489
W. Germany	0.182 (9.324)	0.528 (7.118)	0.709 (9.764)	0.029 (10.016)	0.532
Japan	0.264 (7.472)	0.462 (4.732)	0.726 (8.048)	0.038 (8.584)	0.435
U.K.	0.192 (8.663)	0.513 (6.424)	0.705 (9.014)	0.019 (7.473)	0.597
U.S.	0.214 (8.119)	0.530 (4.702)	0.744 (7.055)	0.017 (7.366)	0.614

Note: Numbers in parentheses are t-ratios.

Table 6.3

Additional Estimated Parameters of the Aggregate Production Functions (at 1970 Values of the Independent Variables)

	F_K	F_L	F_{KK}	F_{LL}	F_{KL}	$\lvert F_{ij} \rvert$	$\frac{\partial \ln K}{\partial \ln r}$	$\frac{\partial \ln(K/L)}{\partial \ln A}$	Elasticity of Substitution
FRANCE	0.154	4.709	-0.228	-53.304	2.210	5.528	-0.224	-0.676	0.324
	(2.196)	(2.191)	(-2.220)	(-1.523)	(2.198)	(0.435)	(-2.071)	(-4.556)	(2.184)
GERMANY	0.057	5.645	-0.029	-46.461	0.735	0.596	-0.341	-0.541	0.459
	(3.808)	(3.771)	(-3.760)	(-1.807)	(3.430)	(0.407)	(-3.365)	(-4.255)	(3.605)
JAPAN	0.340	2.583	-0.603	-12.589	1.857	3.169	-0.248	-0.610	0.390
	(4.827)	(4.207)	(-5.246)	(1.852)	(4.805)	(0.384)	(-2.874)	(-6.016)	(3.839)
U.K.	0.058	3.971	-0.041	-36.241	0.772	0.663	-0.178	-0.755	0.245
	(3.337)	(3.387)	(-3.335)	(-1.781)	(3.196)	(0.423)	(-3.002)	(-9.979)	(3.234)
U.S.	0.157	6.389	-0.059	-19.669	0.728	0.458	-0.349	-0.510	0.490
	(6.589)	(4.606)	(-7.117)	(-1.791)	(4.915)	(0.330)	(-3.596)	(-5.026)	(4.834)

Note: Numbers in parentheses are t-ratios.

Table 7.1

Average Annual Rates of Growth of Real GDP, Capital and Labor

	Period	GDP	Capital Stock	Utilized Capital	Labor Force	Employment	Labor Hours
France	57-85	0.039	0.044	0.043	0.007	0.004	-0.003
W. Germany	60-85	0.029	0.041	0.039	0.002	-0.001	-0.005
Japan	57-85	0.068	0.101	0.101	0.012	0.012	0.007
U.K.	57-85	0.023	0.031	0.031	0.005	0.001	-0.002
U.S.	48-85	0.034	0.033	0.035	0.018	0.017	0.016

Table 7.2

Alternative Estimates of Average Annual Rates of Technical Progress

Country	Conventional Estimates	Our Estimates
France	.019	.031
W. Germany	.014	.027
Japan	.010	.039
U.K.	.013	.018
U.S.	.012	.019

Table 7.3

Relative Contributions of the Sources of Growth

	Capital	Labor	Technical Progress
		This Study	
FRANCE	23	-4	81
W. GERMANY	22	-9	87
JAPAN	39	5	56
UK	25	-5	80
US	23	24	53
		Conventional Estimates	
FRANCE	55	-5	50
W. GERMANY	64	-10	46
JAPAN	80	5	15
UK	54	-6	52
US	40	26	34

Table 8.1

Implied Estimates of the Output-Efficiency Parameters

	$\ln \hat{Y}_0$	$-\ln \hat{A}_{i0}$	$\hat{A}_{i0}$
FRANCE	-0.960 (-218.174)	-0.506 (-142.577)	0.603
W. GERMANY	-0.960 (-218.174)	-0.532 (-163.799)	0.587
JAPAN	-0.960 (-218.174)	-0.536 (-114.056)	0.585
UK	-0.960 (-218.174)	-0.825 (-356.712)	0.438
US	-0.960 (-218.174)	N.A.	1.000

Note: Numbers in parentheses are t-ratios.

Table 8.2

Comparison of Direct and Implied Estimates of a^*_{1i}

	Direct Estimate from production function	Implied Estimate from share equation
FRANCE	0.513 (1.837)	0.175 (47.226)
W. GERMANY	0.513 (1.837)	0.091 (20.952)
JAPAN	0.513 (1.837)	1.309 (403.650)
UK	0.513 (1.837)	0.188 (42.171)
US	0.513 (1.837)	0.245 (139.980)

Note: Numbers in parentheses are t-ratios.

Table A3.1

Comparison of Market and Purchasing Power Parity Exchange Rates in 1980

Country	Local Currency per U.S.$ Market Exchange Rate[1]	PPP Exchange Rate[2]
FRANCE	4.225	5.314
W. GERMANY	1.818	2.456
JAPAN	227.206	248.872
U.K.	0.448	0.503
U.S.A.	1.0	1.0

Notes: [1] International Monetary Fund, <u>International Financial Statistics</u>, period average of market rate (line rf).

[2] Purchasing Power Parity exchange rates for GDP calculated from Summers and Heston (1988).

FIG 6.1: LOCAL RETURNS TO SCALE

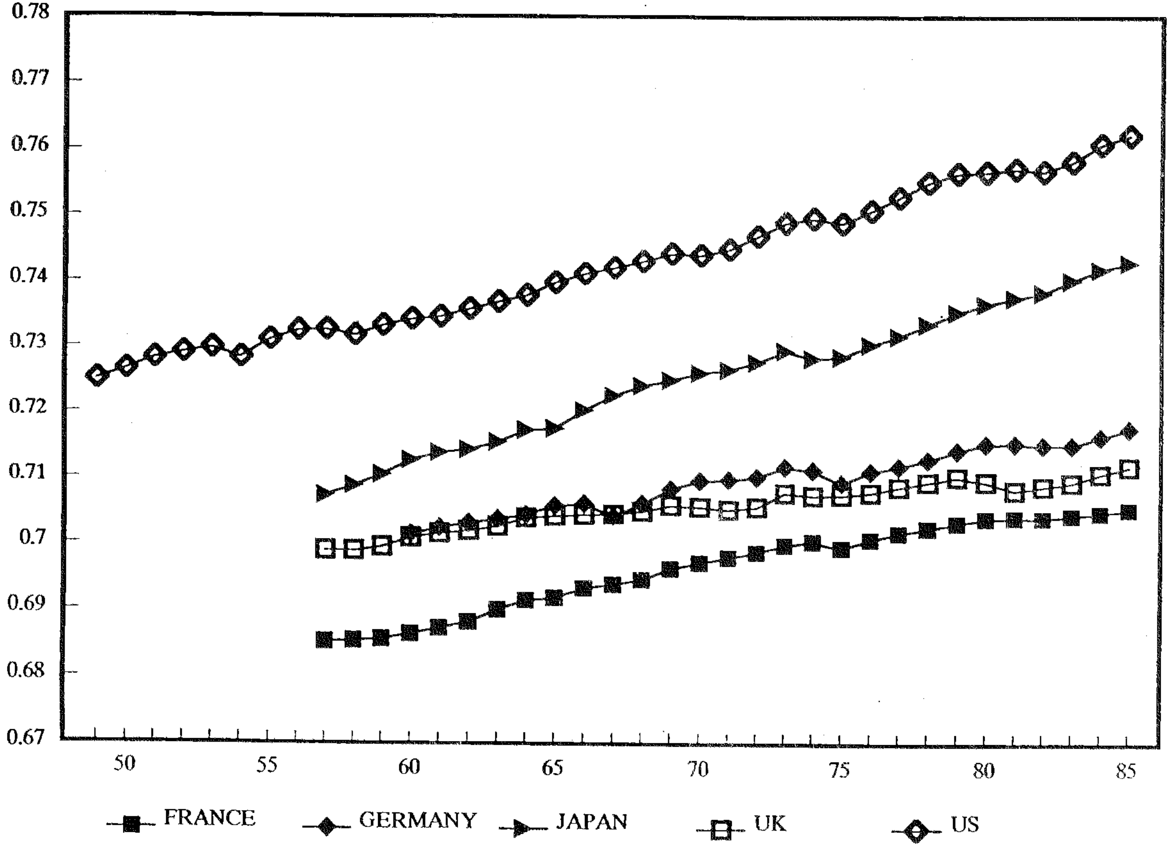


FIG 6.2: LOCAL TECHNICAL PROGRESS

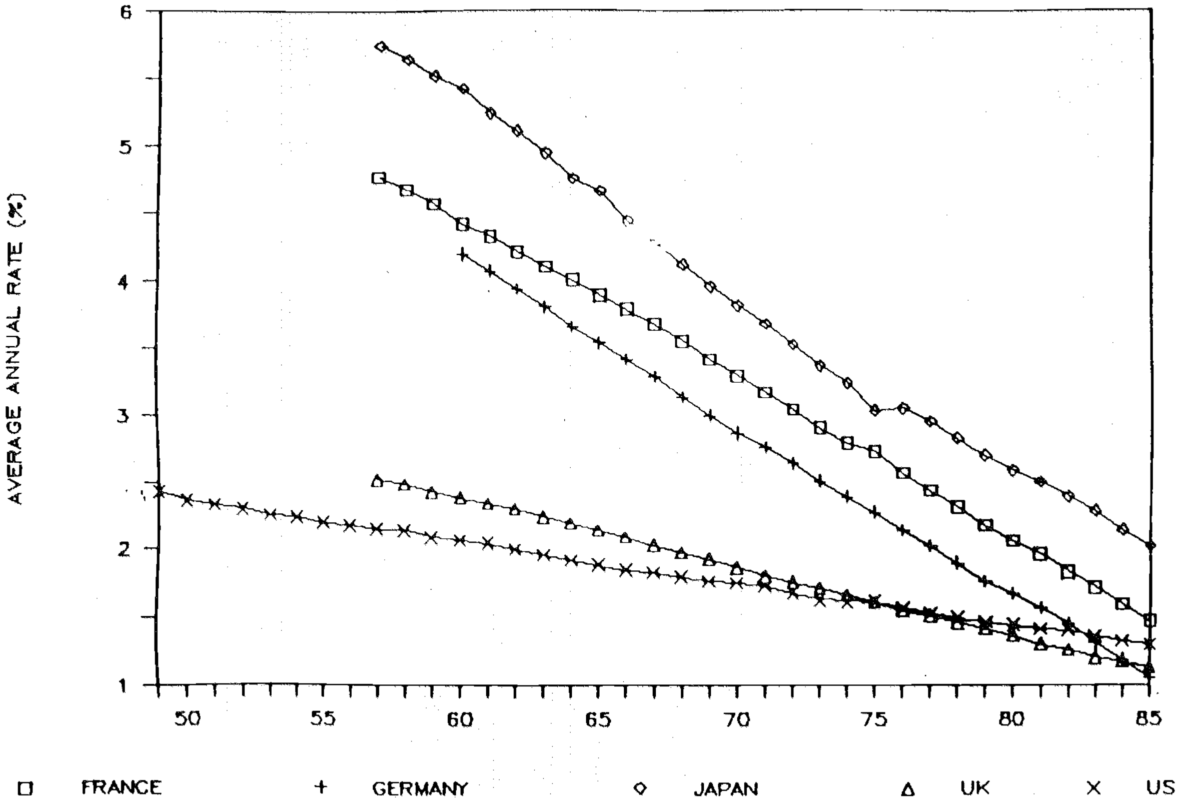


FIG 6.3:ESTIMATED MARGINAL PRODUCTIVITY OF CAPITAL

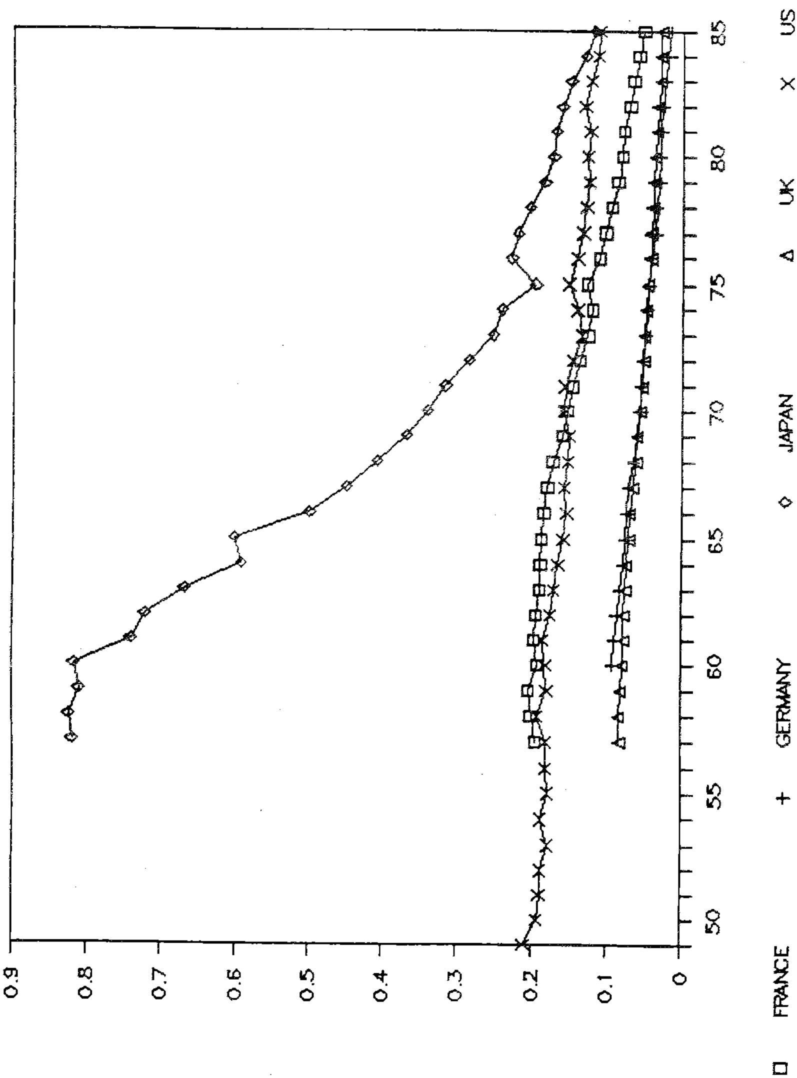


FIG 7.1: CAPITAL AUGMENTATION RATE

VS. CAPITAL GROWTH RATE

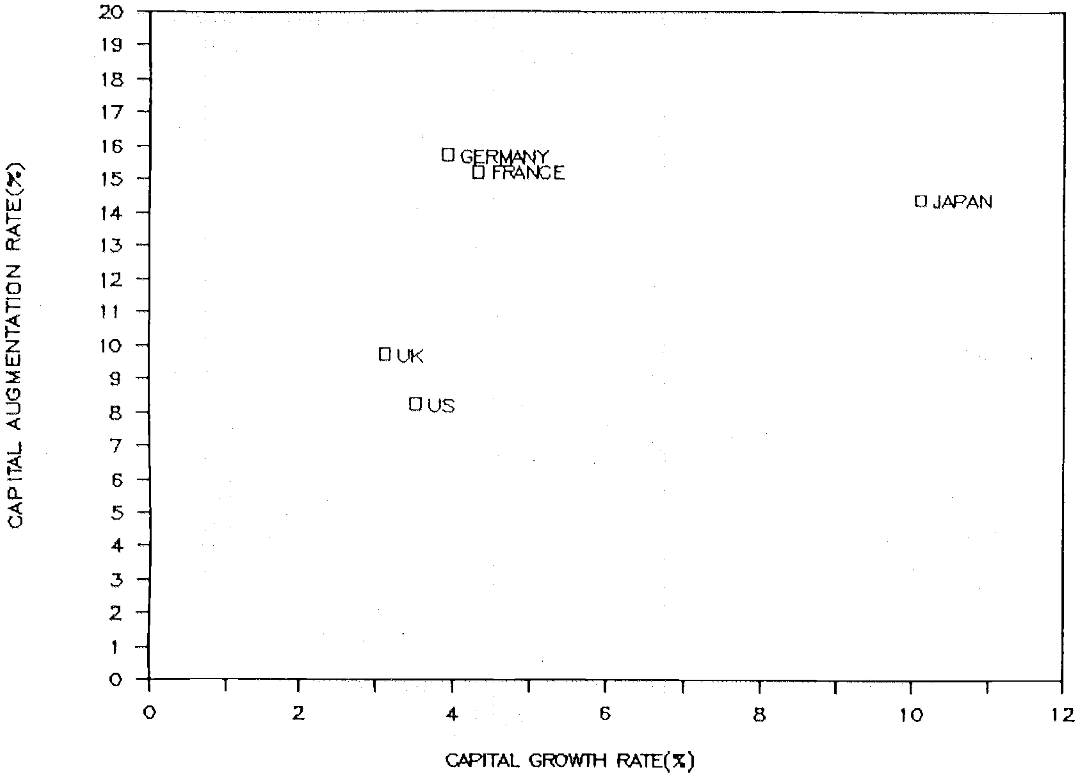


FIG 8.1: REAL OUTPUT PER LABOR-HOUR

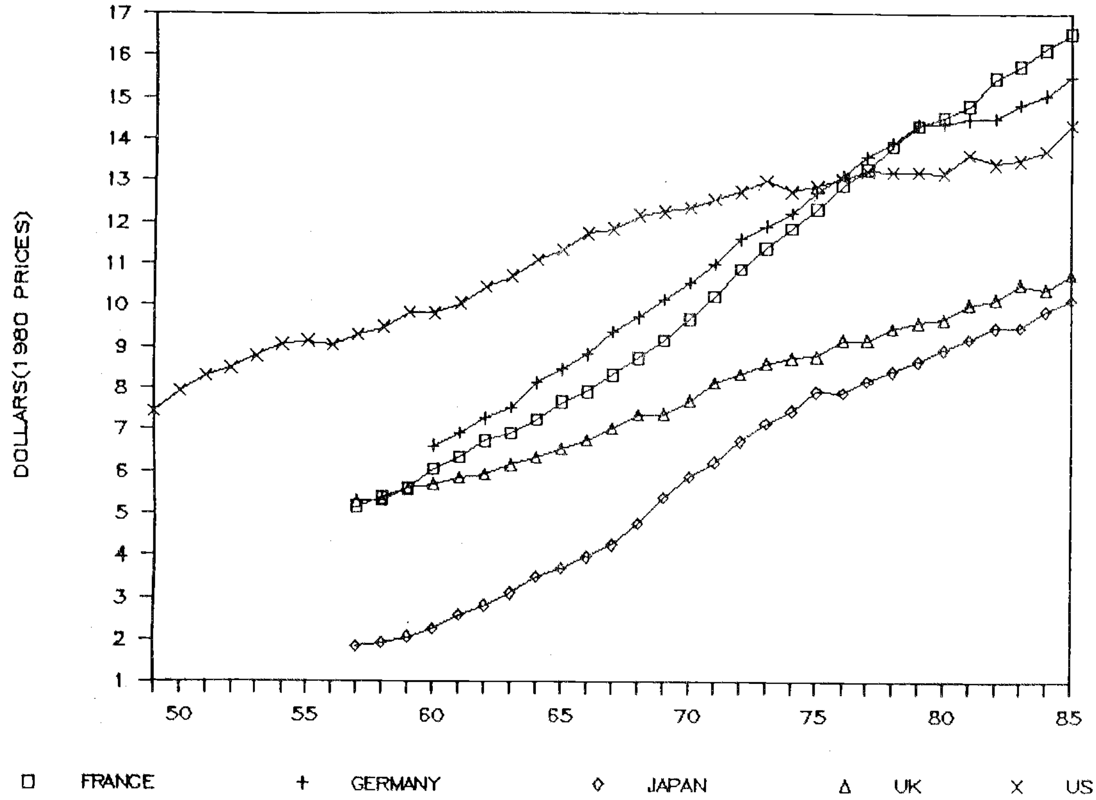


FIG 8.2: CAPITAL STOCK PER WORKER

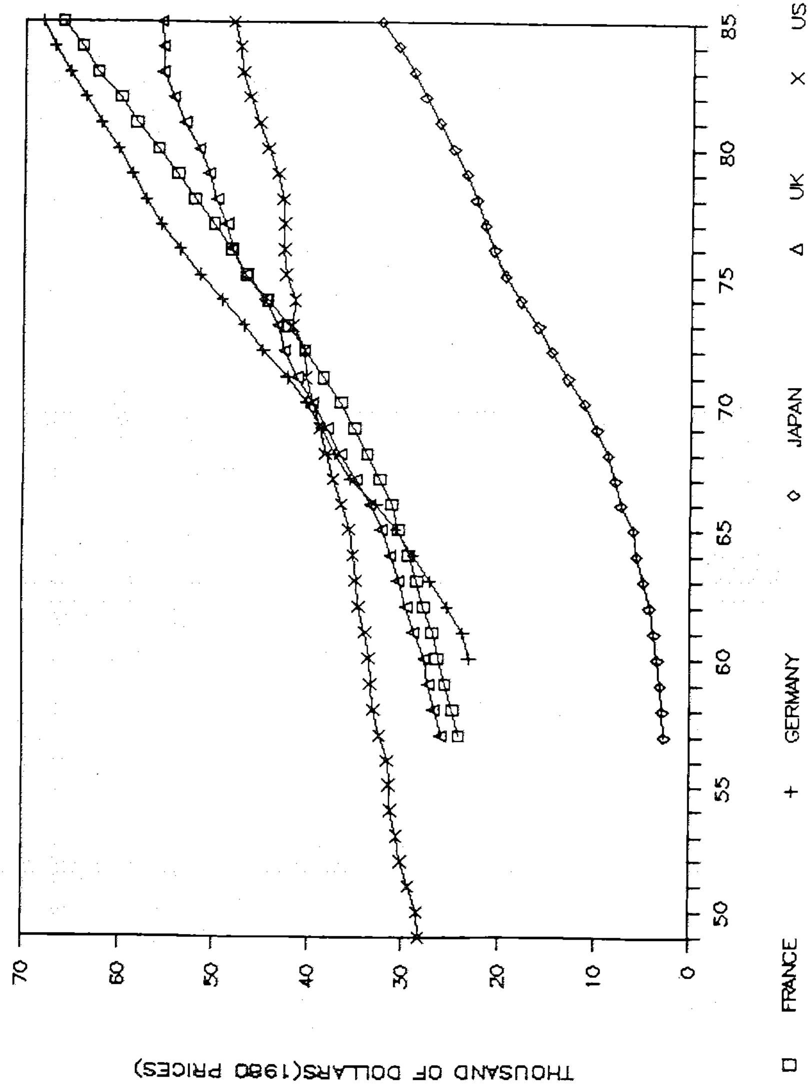


FIG 8.3: REAL OUPPUT

PER UNIT CAPITAL STOCK

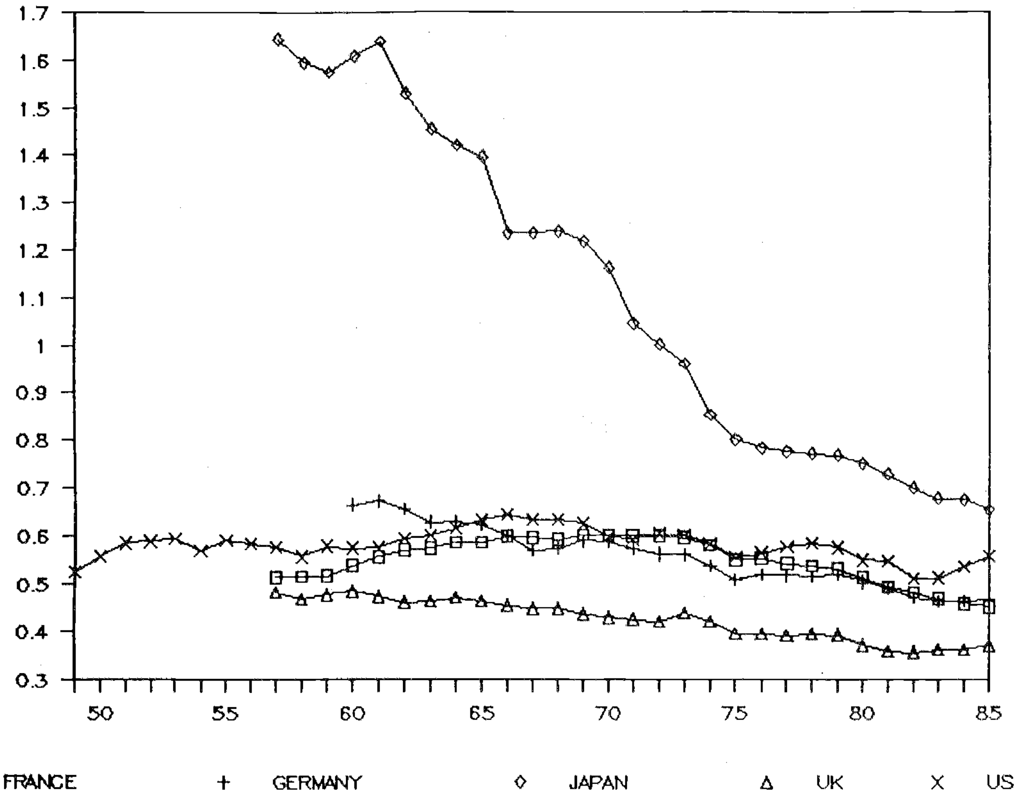


FIG 8.4: REAL OUTPUT OF FRANCE

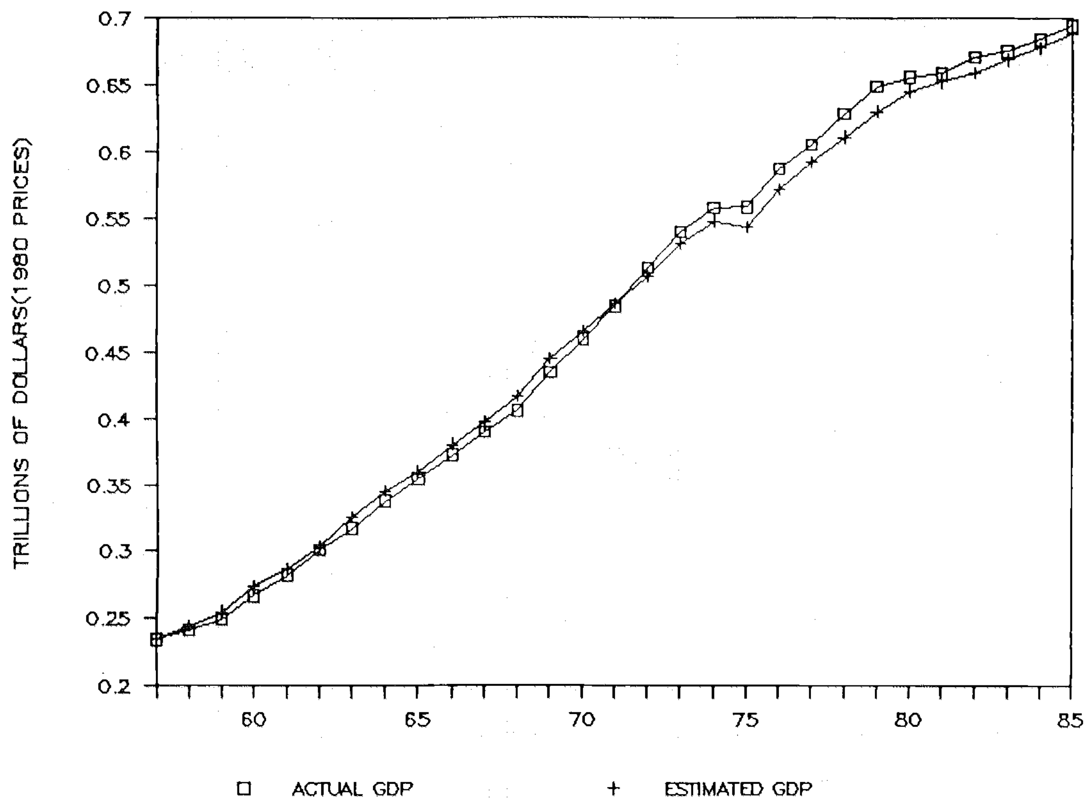


FIG 8.5: REAL OUTPUT OF GERMANY

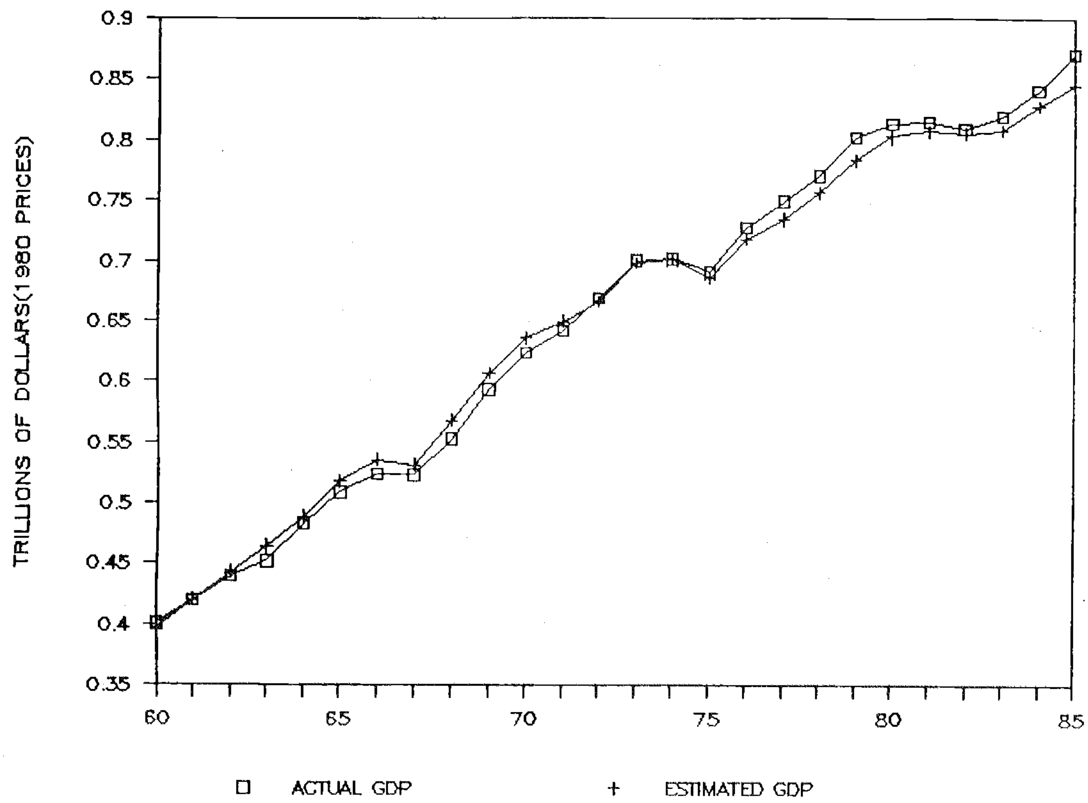


FIG 8.6: REAL OUTPUT OF JAPAN

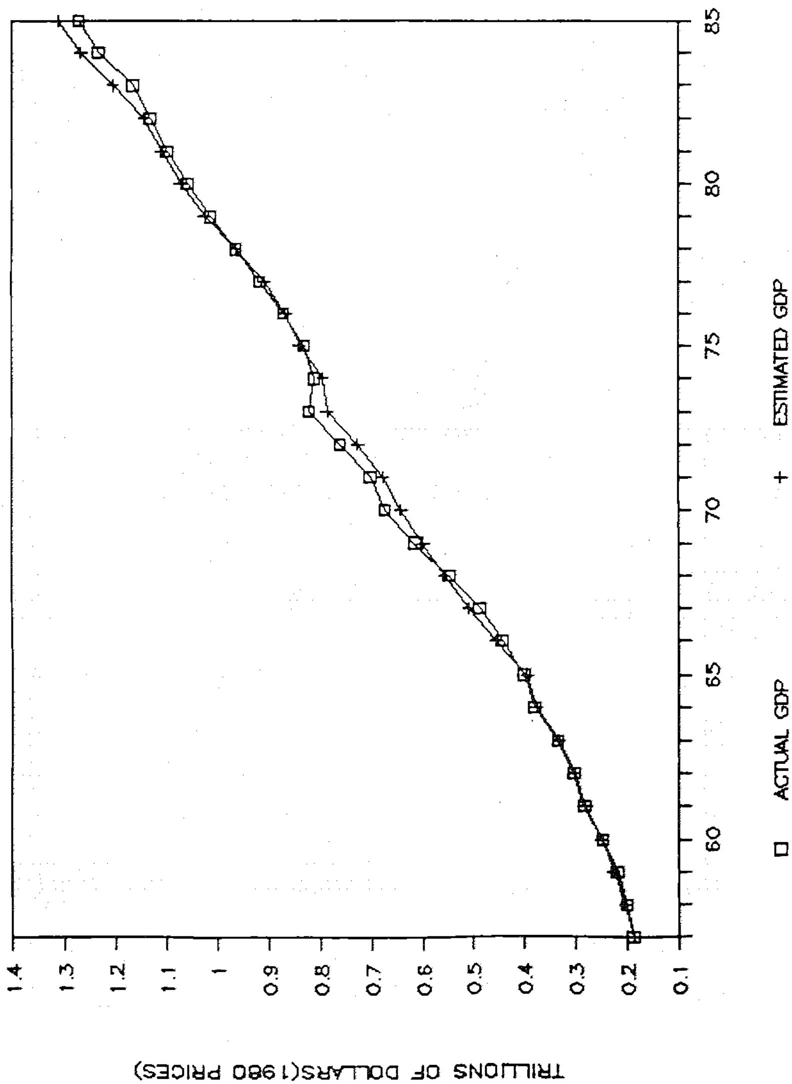


FIG 8.7: REAL OUTPUT OF UK

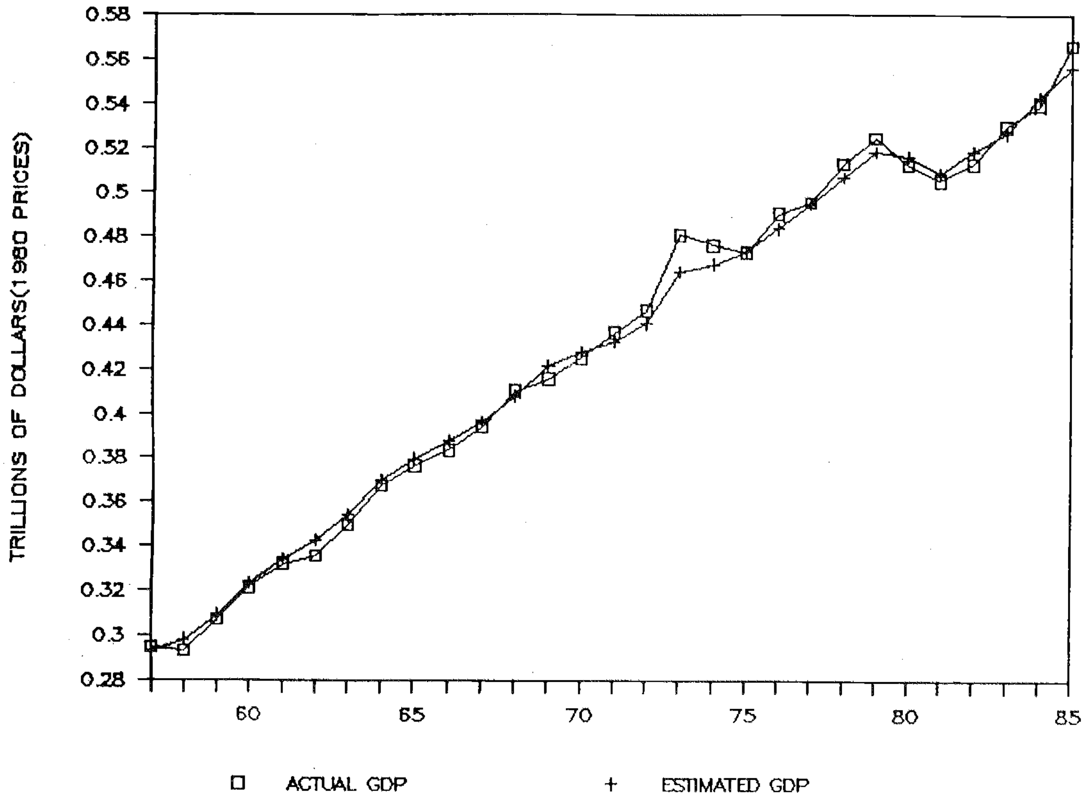


FIG 8.8: REAL OUTPUT OF US

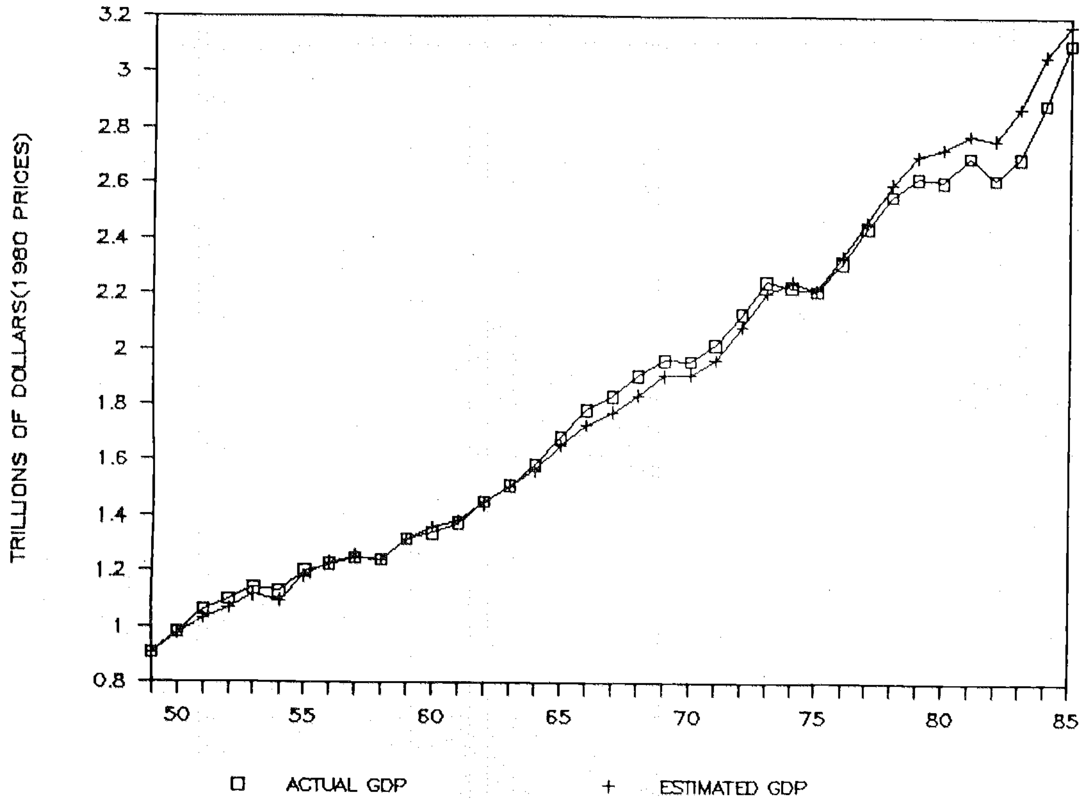


FIG 8.9: HYPOTHETICAL OUTPUT LEVELS OF

COUNTRIES WITH MEASURED INPUTS OF US

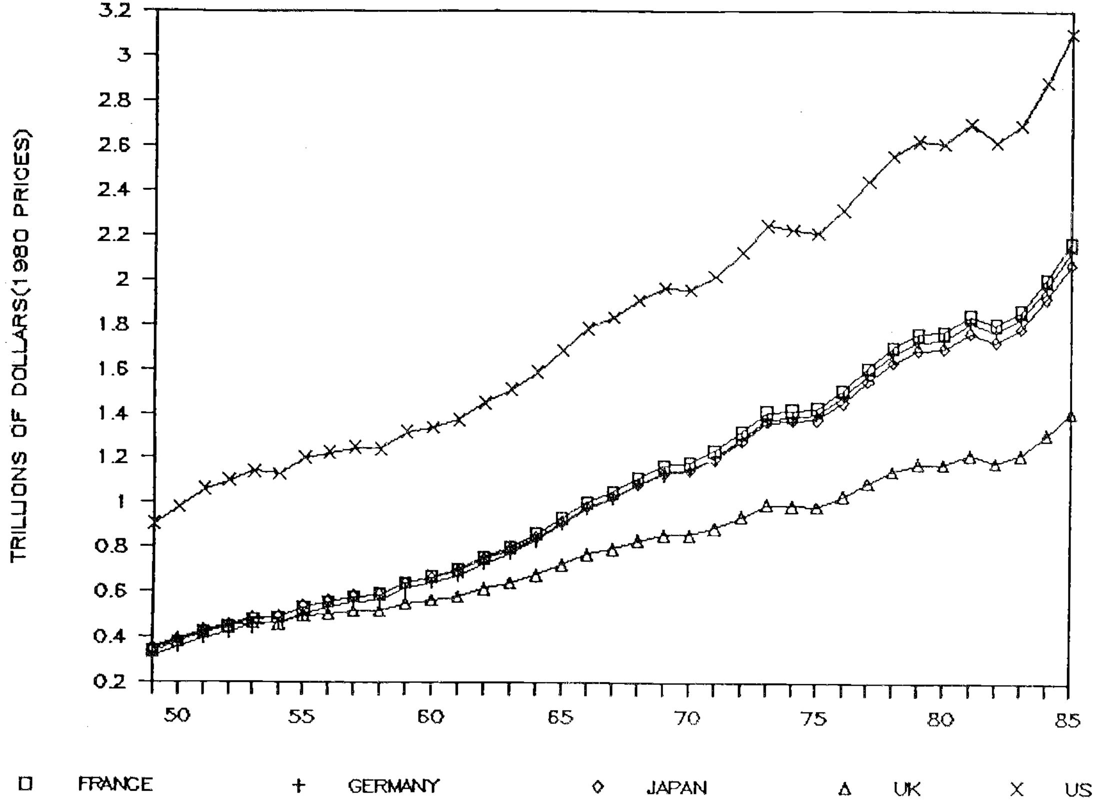


FIG 8.10: PRODUCTIVE EFFICIENCY

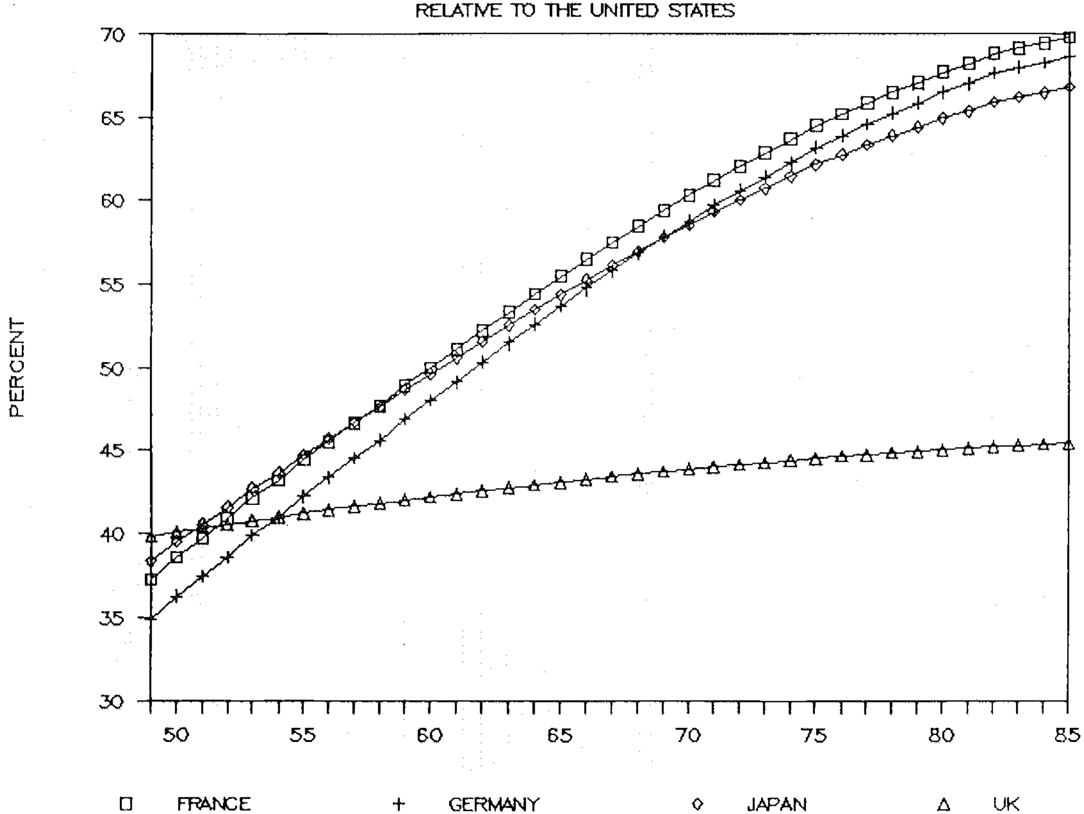
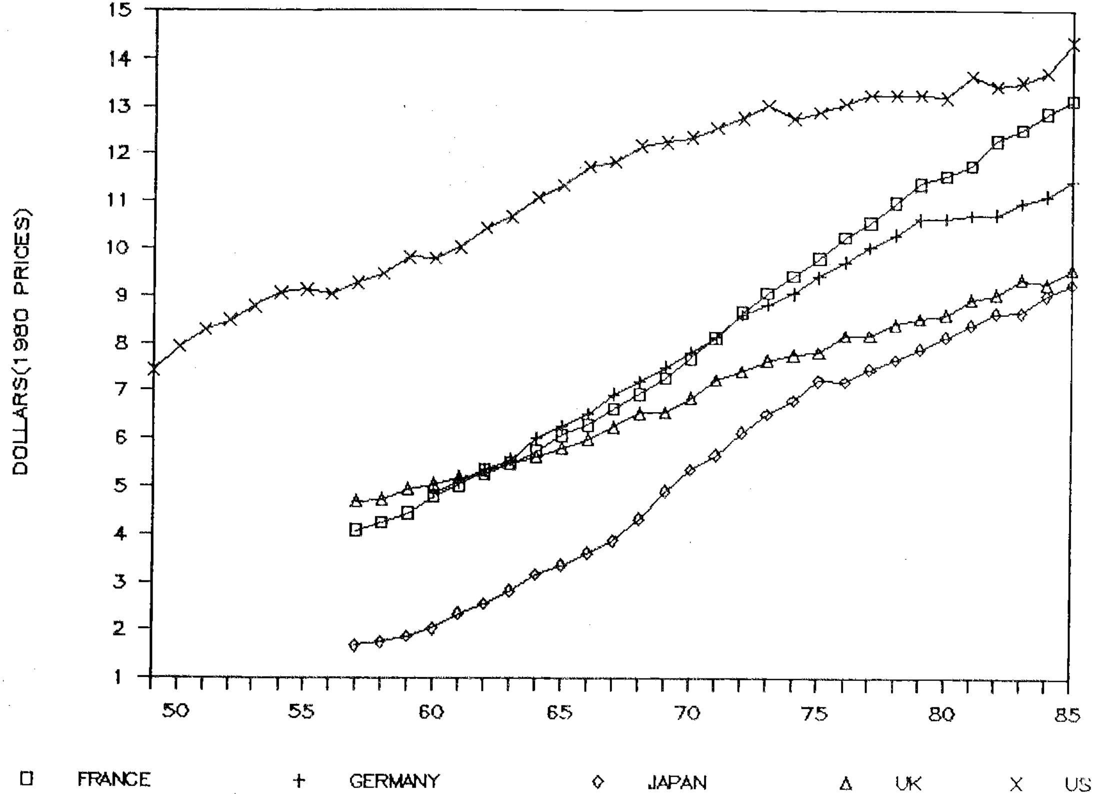


FIG A3.1: REAL OUTPUT PER LABOR—HOUR

(AT PPP EXCHANGE RATES)



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