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GENERALIZED SOLOW-NEUTRAL TECHNICAL PROGRESS AND POSTWAR ECONOMIC GROWTH

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ABSTRACT

Using revised, updated, and consistent annual post-World War II data from the G-7 countries developed by us, we econometrically estimate and test alternative explanations of the structure of economic growth in a model with three inputs – tangible capital, labor, and human capital – which permits the identification of the magnitudes of and biases in both returns to scale and technical progress.

We find:

1. Technical progress is simultaneously purely tangible capital and human capital augmenting, that is, "generalized Solow-neutral." This finding provides an alternative explanation of the slow pace of convergence in real GDP per capita: the benefits from technical progress depend directly on the levels of tangible and human capital; countries with higher levels of capital realize higher rates of technical progress.
2. Technical progress has been capital, not labor, saving and thus is not a cause of systemic structural unemployment.
3. Technical progress accounts for more than 50 percent of the economic growth of the G-7 countries except Canada. Tangible capital input is next most important; together with technical progress, they account for three quarters or more of the growth of real output in the G-7 countries, except Canada.
4. The most important source of the growth slowdown since the mid-1970's, accounting for between one-third and one-half, is a decline in the rate of capital (both tangible and human)-augmenting technical progress.

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1. Introduction and Overview

Among the most important empirical economic phenomena of the post-World War II period are the sharp deceleration of economic growth in the industrialized countries beginning around the early 1970's relative to the previous quarter century, and the relatively slow pace of convergence of per capita incomes among countries. In Table 1.1, we present the rates of growth of real GDP of the Group-of-Seven (G-7) countries (Canada, France, West Germany, Italy, Japan, United Kingdom and United States) in both aggregate and per capita terms, for the periods before and after the oil price shock of 1973. It is clear from Table 1.1 that there was a significant slowdown in the rates of growth in the G-7 countries in the second period compared to the first (even in the U.S., despite the recent uptick the permanence of which remains to be seen). Moreover, it is also clear that the differences in the rates of growth in real GDP per capita, between the United States, the leading economy, and the other G-7 economies, narrowed considerably in both absolute and relative terms, in the second period compared to the first. In fact, both Canada and France had lower rates of growth than the United States in the second period. What this indicates is that while there was a strong tendency for convergence in real GDPs per capita in the early postwar period up to 1973, the process appeared to have slowed considerably, if not halted, since then, at least relative to the U.S.[1]

These two apparent long-term trends have been important motivators of much recent research on economic growth, in both the more standard growth accounting and econometric literature (e.g., Gordon (2000), Jorgenson (1995a, 1995b), Jorgenson and Stiroh (2000), Maddison (1987)), and the new growth theory and related cross-country empirical studies (e.g., Romer (1986, 1987, 1990), Barro (1991), Barro and Sala-i-martin (1995), Lucas (1988), Mankiw, Romer and Weil (1992)). The latter lines of work emphasize the potential roles of increasing returns from ideas, human

[1] See Baumol (1986) for a discussion of the very long-run tendency toward convergence among the industrialized countries.

Table 1.1: Rates of Growth of Real GDP and Real GDP per Capita of Group-of-Seven (G-7) Countries (percent per annum)				
	Sample Period	Entire Period	First Period	Second Period
			~1973	1973~
Real GDP				
Canada	58-97	3.54	4.75	2.91
France	58-97	3.25	5.09	2.15
W. Germany	58-94	3.28	4.76	2.26
Italy	60-97	3.41	5.31	2.46
Japan	58-97	5.56	9.40	3.36
U.K.	58-97	2.47	3.26	2.13
U.S.A.	50-98	3.54	4.19	3.07
Real GDP per Capita				
Canada	58-97	2.13	3.29	1.78
France	58-97	2.53	4.03	1.65
W. Germany	58-94	2.70	3.82	1.95
Italy	60-97	2.97	4.54	2.20
Japan	58-97	4.78	8.17	2.69
U.K.	58-97	2.14	2.71	1.95
U.S.A.	50-98	2.30	2.70	2.06

capital and network externalities. In this study, we apply an aggregate production function approach to the analysis of postwar economic growth in the G-7 countries that is sympathetic, at least partly, to both of these lines of work. It generalizes the former potentially to allow for increasing returns and biased technical progress and explicitly incorporates human capital as a third input. The framework used 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. Our objectives in this study, using this new framework, are first, to make a new assessment of the relative contributions of capital, labor, human capital and technical progress to post-World War II economic growth and its slowdown in the industrialized countries; and second, to analyze the nature of the technical progress and scale economies, if any, in these countries.

We find that technical progress is simultaneously purely capital-augmenting and purely human capital-augmenting--which we shall refer to as "generalized Solow-neutrality"--implying that the effect of technical progress depends upon the level of capital and human capital stocks in an economy—in contrast to the hypothesis of "labor-augmenting" or "Harrod-neutral" technical progress conventionally adopted in almost all theoretical models of economic growth. The fact that technical progress is capital (and human capital)-augmenting provides an alternative explanation of the slow pace of convergence. The empirical findings of our growth-accounting exercises also provide insight into the proximate causes of the growth slowdown from a long enough perspective to place the 1970's oil shocks in their limited perspective: a slower pace of both capital formation and technical progress is the primary culprit. For the postwar period as a whole and for each of the sub-periods, however, technical progress is the most important source of economic growth; it accounts for over half of economic growth in each of the G-7 countries except Canada where it accounts for slightly less than a quarter.

In section 2, we briefly describe our model, including the stochastic specification, and the data. In section 3, we present the results of our hypothesis testing. In section 4, we discuss the implications of technical progress being simultaneously purely capital-augmenting and purely human capital-augmenting. In section 5, we present the estimated aggregate meta-production functions as well as other parameters of interest. In section 6, we carry out a growth accounting exercise based on our estimates and compare our results with those using the traditional approach. In section 7, the sources of the measured growth slowdown since the mid-1970s are also identified. Finally, some concluding remarks are made in section 8.

2. The Model and the Data

We estimate an aggregate "meta-production function" from pooled multi-country time-series data.[2] The basic assumptions for this approach are:

(1) All countries have the same underlying aggregate production function F(.) in terms of standardized, or "efficiency-equivalent" quantities of outputs and inputs, that is:

[2] The term "meta-production function" is due to Hayami and Ruttan (1970). The approach used here is based on the extension by Lau and Yotopoulos (1989). It is discussed in some detail in Boskin and Lau (1990).

(2.1) $Y_{it}^{*} = F(K_{it}^{*}, L_{it}^{*}, H_{it}^{*}), i = 1,\ldots,n;$

where Y^{*}_{it}, K^{*}_{it}, L^{*}_{it} and H^{*}_{it} are the "efficiency-equivalent" quantities of output, capital, labor and human capital respectively of the ith country in year t, and n is the number of countries.[3]

(2) The unobservable "efficiency-equivalent" quantities of output and inputs of each country are linked to the measured quantities of outputs, Y_{it}'s, and inputs, K_{it}'s, L_{it}'s and H_{it}'s, through multiplicative, country- and commodity-specific, time-varying augmentation factors $A_{ij}(t)$'s, i = 1,...,n; j = 0 (output), K (capital), L (labor), and H (human capital). It is assumed that these augmentation factors have the constant geometric form; for example:

(2.2) $K_{it}^{*} = A_{iK}(1 + c_{iK})^{t} K_{it}; i = 1,\ldots,n,$[4]

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.

There are many reasons why these commodity augmentation factors are not likely to be identical across countries. Differences in climate, geography, topography and infrastructure;[5] differences in endowments and resources (and more generally unmeasured inputs); 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, as well as the evolution of these differences over time, across countries.[6] [7]

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[3]In this study, it is assumed that $F(\cdot)$ depends on t only through the commodity-augmentation factors; in other words, $F(\cdot)$ does not depend directly on t.

[4]Thus, measured inputs of any country may be converted into equivalent units of measured inputs of another country. For example, one unit of capital in country A may be equivalent to two units of capital in country B; and one unit of labor in country A may be equivalent to one-third of a unit of labor in country B. Moreover, these conversion ratios may change over time.

[5] See Hall and Jones (1999) and Sachs and Warner (1995).

[6] For at least one country, say the ith, the constants A_{i0} and A_{ij}'s can be set identically at unity, reflecting the fact that "efficiency-equivalent" outputs and inputs can be measured only relative to some standard. Without loss of generality we take the Ai0 and Aij's for the United States to be identically unity.

(3) The aggregate meta-production function is assumed to have the transcendental logarithmic (translog) functional form introduced by Christensen, Jorgenson and Lau (1973).

The use of the translog functional form allows us to identify both the magnitudes and biases of the degree of returns to scale and technical progress. With a Cobb-Douglas production function, it is impossible to identify any of the biases: Solow-neutral technical progress will have the same empirically observable implications as Hicks-neutral or Harrod-neutral technical progress. Moreover, the flexibility of the translog function can better accommodate the wider ranges of data variation due to the pooling of data across the G-7 countries. However, it is the diversity of these economies in terms of their tangible capital to labor ratios and human capital development that enables the identification and estimation of the biases, if any, in returns to scale and in technical progress.

By substituting equations such as (2.2) into a translog production function specified in terms of the efficiency-equivalent units of outputs and inputs, and simplifying, we obtain equation (2.3), which is written entirely in terms of observable variables:

(2.3)
$$\begin{aligned}\ell n Y_{it} = {} & \ell n Y_0 + \ell n A_{i0}^{*} + a_{Ki}^{*} \ell n K_{it} + a_{Li}^{*} \ell n L_{it} + a_{Hi}^{*} \ell n H_{it} + c_{i0}^{*} t \\ & + B_{KK} (\ell n K_{it})^2/2 + B_{LL} (\ell n L_{it})^2/2 + B_{HH} (\ell n H_{it})^2/2 \\ & + B_{KL} (\ell n K_{it})(\ell n L_{it}) + B_{KH} (\ell n K_{it})(\ell n H_{it}) + B_{LH} (\ell n L_{it})(\ell n H_{it}) \\ & + (B_{KK} \ell n(1+c_{iK}) + B_{KL} \ell n(1+c_{iL}) + B_{KH} \ell n(1+c_{iH}))(\ell n K_{it}) t \\ & + (B_{KL} \ell n(1+c_{iK}) + B_{LL} \ell n(1+c_{iL}) + B_{LH} \ell n(1+c_{iH}))(\ell n L_{it}) t \\ & + (B_{KH} \ell n(1+c_{iK}) + B_{LH} \ell n(1+c_{iL}) + B_{HH} \ell n(1+c_{iH}))(\ell n H_{it}) t\end{aligned}$$

[7] However, the meaning of these augmentation rates must be interpreted very carefully. For example, an increase in computer literacy may be reflected as an augmentation of tangible capital (an increase in the effective number of computers) rather than labor.

$$+ (B_{KK}(\ell n(1+c_{iK}))^2 + B_{LL}(\ell n(1+c_{iL}))^2 + B_{HH}(\ell n(1+c_{iH}))^2 + 2B_{KL}(\ell n(1+c_{iK}))(\ell n(1+c_{iL}))$$

$$+ 2B_{KH}(\ell n(1+c_{iK}))(\ell n(1+c_{iH})) + 2B_{LH}(\ell n(1+c_{iL}))(\ell n(1+c_{iH})))t^2/2, i = 1,...n,$$

where A^*_{i0}, a^*_{Ki}, a^*_{Li}, a^*_{Hi}, c^*_{i0} and c_{ij}'s , j = K, L, and H, are country-specific constants. Equation (2.3) is the most general specification possible under our maintained hypotheses of a single meta-production function and constant geometric commodity-augmentation representation of technical progress.

In addition to the aggregate meta-production function, we also consider the behavior of the share of total labor costs in the value of output—$w_{it}L_{it}/p_{it}Y_{it}$—where w_{it} is the nominal wage rate (including fringe benefits) and p_{it} is the nominal price of output in the ith country in year t, as a function of measured capital, labor, human capital inputs, and time:

$$(2.4) \qquad \frac{w_{it}L_{it}}{p_{it}Y_{it}} = a_{Lii}^* + B_{KLi}\ell nK_{it} + B_{LLi}\ell nL_{it} + B_{LHi}\ell nH_{it} + B_{Lti}t, i = 1,..., n.$$

Under the assumption of profit maximization under competitive output and input markets, the labor share should be equal to the sum of the elasticities of output with respect to labor and human capital, which implies restrictions between the parameters of the labor share equation and the production function.[8]

In equations (2.3), it is assumed that there is a single rate of augmentation for each commodity and country for the entire period. It is of course completely possible that the rates of augmentation may change over time, e.g., reflecting the oil price shock of the 1970s and the oil price decline in the mid-1980s. We allow for this possibility in our empirical implementation discussed below.

The Stochastic Specification

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[8] The restrictions are: $a_{Lii}^* = a_{Li}^* + a_{Hi}^*$, $B_{KLi} = B_{KL} + B_{LH}$, $B_{LLi} = B_{LL} + B_{LH}$, $B_{LHi} = B_{LH} + B_{HH}$, and $B_{Lti} = (B_{KL} + B_{KH})\ell n(1+c_{iK}) + (B_{LL} + B_{LH})\ell n(1+c_{iL}) + (B_{LH} + B_{HH})\ell n(1+c_{iH})),$ i = 1,...,n.

We introduce stochastic disturbance terms ε_{1it}'s and ε_{2it}'s into the natural logarithm of the aggregate production function and the labor share equation, respectively. We assume

$$E\begin{bmatrix}\varepsilon_{1it}\\ \varepsilon_{2it}\end{bmatrix} = 0, \forall i, t;$$

$$V\begin{bmatrix}\varepsilon_{1it}\\ \varepsilon_{2it}\end{bmatrix} = \sum, \text{a constant, nonsingular matrix, } \forall i, t;$$

and the stochastic disturbance terms are uncorrelated across countries and over time. They are introduced additively to the first-differenced forms of the aggregate production function and the labor share equation. Under the further assumption of joint normality of the stochastic disturbance terms, the system of two equations consisting of the production function and the labor share equation and its various specializations are estimated by the method of nonlinear instrumental variables.[9] The list of instruments used is presented below.

The Data

We use the most recent comprehensive data available from the G-7 countries: Canada, France, West Germany, Italy, Japan, the United Kingdom and the United States. The period covered is from 1958 to 1997 except for West Germany (1958-1994)[10], Italy (1960-97), and the U.S. (1950-98). In order to estimate the production function (2.3) and the share equation (2.4), the measurements of five variables--Y, K, L, H and the labor share wL/pY--are needed. Output, Y, is measured as real GDP and is taken from OECD, National Accounts, and the National Income and Product Accounts of the United States. A comprehensive and consistent method was used to splice the data from available historical series so as to maximize their comparability to the most recent data revisions. Capital stock is measured as the total non-residential gross capital stock, derived by the perpetual inventory method from the most recent gross

[9]See, e.g., Gallant and Jorgenson (1979).

[10] The sample period for West Germany ends in 1994 because data on West Germany alone after 1994 are no longer available. Only data on a unified Germany are available.

fixed investment series from the national income accounts.[11] [12] The capital variable, K, is taken as the utilized capital stock--the capital stock at the beginning of a calendar year multiplied by the capacity utilization rate. Labor, L, is measured as the total number of labor-hours worked; the data are based on OECD, Labor Force Statistics, and U.S. Department of Labor, Bureau of Labor Statistics (1999). Human Capital, H, defined as the total number of years of formal education of the working age (15-64, inclusive) population at the beginning of the calendar year, is derived from annual time-series data on educational enrollment and population, using the perpetual inventory method. Y and K are converted into 1990 U.S. dollars using the 1990 PPP exchange rates published by OECD.[13] The share of labor in the value of output, wL/pY, is estimated by dividing the current labor income in current prices (adjusted to include part of proprietors' income) by the GDP in current prices of each country. The instrumental variables used in the estimation include: real output lagged one and two periods, lagged tangible and human capital stocks, lagged labor force, country dummy variables, 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

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[11] We use gross rather than net capital stock for all countries other than the U.S. because comparable and consistent data series are available across them only for gross capital stock. For the U.S., we use both the net capital stock from the most recent comprehensive NIPA revision and the gross stock (no longer available) through 1997 for comparison purposes. However, given that we are attempting to estimate the rates of capital augmentation, our estimated rates may be interpreted as the rates of capital augmentation net of the rates of depreciation. If net capital stocks are used the estimated rates would have been higher by amounts equal to the rates of depreciation.

[12] We use the aggregate value of the capital stock at constant prices, which is the form in which the capital stock data are generally available. For a discussion and justification of this approach, see Lau (2000).

[13] We have made explicit purchasing-power-parity (PPP) adjustments to the data using the 1990 PPP exchange rates published by OECD. 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 1990 in the conversion of the investment and GDP data from constant local currency to constant U.S. dollars has no effect on our results except the estimates of the augmentation level parameters. 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.

ore, and finally the time as well as dummy variables indicating possible discontinuities and breaks in trends.[14]

We present a summary of the data on the seven countries between 1960 and 1997 (1994 for West Germany) in Tables 2.1 and 2.2. Table 2.1 shows that in 1997, the United States has the highest real GDP, followed by Japan, West Germany, France, the U.K., Italy and Canada. However, in 1960, West Germany was in second place, followed by the U.K., France, Japan, Italy and Canada. In other words, Japan has moved up, and the U.K. has moved down. This switch in the ranking should not be surprising, since Japan had the highest average annual rate of growth of real GDP, 5.6 percent, whereas the other G-7 countries had average annual rates of growth ranging between 2.5 and 3.6 percent, with the United Kingdom the lowest, during this period. Japan also had the highest rate of growth of the capital stock. During this period, Canada had the highest rate of growth of the working age population, the labor force, employment and total labor hours, followed by the United States, due to the postwar baby boom, continuing significant immigration, and the rise in the female labor force participation rate. The European G-7 countries had a significantly lower rate of growth of the working age population, the labor force, and employment compared to the others. Given the worldwide trend of a declining length of the average work week, the European G-7 countries actually experienced declines in labor input in the postwar period. Canada also had the highest rate of growth of human capital, followed by the United States and France. However, the rates of growth of the European G-7 countries were not appreciably lower with the exception of the U.K.

Table 2.2 shows that even though the United States had by far the highest real GDP per capita in 1997, it had only marginally higher real GDP per labor-hour than Italy, France and Germany. However, in the case of Italy, it is believed that labor hours are significantly under-counted, much more than in the other G-7 countries, because of the size and significance of its underground economy (see Schneider and Enste (2000)). After this group came Canada and the U.K. Japan had the lowest real GDP per labor-hour, partly because it had the highest average hours per worker among the G-7 countries. However, back in 1960, the

[14] More details on the construction of each of these variables and the sources used for the construction of

U.S. was first, followed closely by Canada, far ahead of Europe, with Japan in last place. The European G-7 countries, with the exception of the U.K., have essentially moved to a level of productivity, measured in terms of real output per labor-hour, that is very comparable to that of the United States. Capital intensity, measured as utilized capital per labor-hour, also followed a similar pattern. In 1960, the United States had the highest tangible capital-labor ratio and Japan the lowest. Over time, the continental European countries and Japan have overtaken the U.S. in terms of capital intensity. By 1997, Canada had the lowest tangible capital-labor ratio and the U.S. the second lowest. This relative decline in the capital intensity in the United States and Canada reflects in part that they are the only G-7 countries with a significant growth in the labor force, employment, and total labor hours.

Japan had the highest labor force participation rate in 1960 and continued to do so in 1997. Canada, which had the lowest labor force participation rate in 1960, overtook all of the European G-7 countries except the U.K. by 1997. In fact, Canada and the U.S. had the highest rate of growth in the labor force participation rate. They are also the only countries with an increase in the employment rate (defined as the ratio of employment to labor force, or equivalently, one minus the unemployment rate). All the other G-7 countries showed significant increases in their unemployment rates, with the Europeans switching places relative to the U.S. The average hours worked per worker declined in all countries but the declines were the slowest in Canada, the U.K. and the U.S.

In terms of average years of schooling of the working-age population, the United States has continued to maintain its commanding lead since 1948. It is still more than one whole year ahead of Canada and West Germany, which are in second and third places. In the 1990s, Italy, which used to have the lowest average years of schooling, surpassed the U.K., which replaced Italy as the country with the lowest average years of schooling. Italy also has the highest rate of growth of average schooling, followed by France, Canada and West Germany. Average schooling in the other countries--Japan, the U.K. and the U.S.--have

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the data are contained in a data appendix available from the authors.

all been growing at the same rate. If the current trend continues, the U.K. is likely to be left behind in terms of human capital.

Table 2.1: The Levels and Average Annual Rates of Growth of Selected Aggregate Variables of the Group-of-Seven (G-7) Countries

Levels in 1960 and 1997

	Real GDP (Tril. 1990 US$)		Utilized Capital[1] (Tril. 1990 US$)		Human Capital[2] (Mil. Sch. Yrs.)		Total Labor Hours (Bil. Hrs.)		Average Hours Worked Per Year (Thou.)		Employment (Mil.)		Labor Force (Mil.)		Working Age Population (Mil.)	
	1960	1997	1960	1997	1960	1997	1960	1997	1960	1997	1960	1997	1960	1997	1960	1997
Canada	0.159	0.581	0.178	1.051	90.0	253.0	11.4	23.3	1.916	1.768	5.76	13.17	6.41	14.58	10.79	20.57
France	0.340	1.077	0.355	2.080	224.1	457.2	39.4	37.2	2.120	1.688	18.61	22.03	18.89	25.22	28.32	38.30
W.Germany[3]	0.460	1.244	0.613	2.727	329.0	546.4	51.7	46.0	1.969	1.623	26.25	28.32	26.52	30.87	37.60	45.03
Italy	0.302	0.997	0.416	2.335	218.2	417.9	37.8	33.8	1.925	1.629	19.62	20.73	20.84	24.19	33.25	40.20
Japan	0.364	2.483	0.330	7.151	524.6	1048.8	105.7	125.3	2.383	1.911	44.36	65.57	45.11	67.87	59.37	87.04
U.K.	0.436	1.033	0.637	2.401	259.5	391.1	47.0	46.8	1.982	1.758	23.71	26.63	24.07	28.22	34.20	37.82
U.S.	2.056	7.046	3.818 (3.178)[4]	12.725 (9.481)[4]	1138.5	2279.9	136.5	237.2	2.076	1.860	65.78	127.49	69.63	134.37	107.93	175.36

Average Annual Rates of Growth (percent per annum)

	Period	Real GDP	Utilized Capital	Human Capital	Total Labor Hours	Average Hours/Worker	Employment	Labor Force	Working Age Population
Canada	60-97	3.6	4.9	2.9	1.9	-0.2	2.2	2.3	1.8
France	60-97	3.3	5.0	2.0	-0.1	-0.6	0.5	0.8	0.8
W.Germany	60-94	3.2	4.7	1.5	-0.3	-0.6	0.3	0.5	0.5
Italy	60-97	3.4	5.0	1.8	-0.3	-0.4	0.2	0.4	0.5
Japan	60-97	5.6	8.8	1.9	0.5	-0.5	1.1	1.1	1.0
U.K.	60-97	2.5	3.8	1.1	0.0	-0.3	0.4	0.5	0.3
U.S.	60-97	3.4	3.3 (2.1)[4]	2.0	1.5	-0.3	1.8	1.8	1.3

Notes: 1. Utilized capital is gross tangible capital stock times the utilization rate.
2. Human capital is average years of schooling per person times working age population.
3. Data for West Germany are only available through 1994.
4. Numbers in parentheses refer to utilized net tangible capital stocks.

Table 2.2: The Levels and Average Annual Rates of Growth of Selected Ratios of he Group-of-Seven (G-7) Countries

	Output per Capita (1990 US$)		Output per Labor-Hour (1990 US$)		Physical Capital per Labor-Hour (1990 US$)		Human Capital per Working-Age Pop. (Years)		Average Hours Worked per Worker per Year (Thou.)		Employment Rate (%)		Labor Force Participation Rate (%)		Female Labor Force Participation Rate (%)	
Levels																
	1960	1997	1960	1997	1960	1997	1960	1997	1960	1997	1960	1997	1960	1997	1960	1997
Canada	8916	20206	13.94	24.96	19.09	53.18	8.34	12.38	1.916	1.768	89.9	90.3	59.4	70.9	30.1	57.4
France	7441	18404	8.62	28.95	11.46	68.02	7.91	12.14	2.120	1.688	98.5	87.4	66.7	65.9	38.2	47.9
W.Germany[1]	8298	18846	8.90	27.06	13.40	71.68	8.75	12.26	1.969	1.623	99.0	91.7	70.5	68.6	41.1	44.1
Italy	6169	17448	8.00	29.51	13.58	88.95	6.56	10.64	1.925	1.629	94.1	85.7	62.7	60.2	32.3	34.7
Japan	3899	19693	3.44	19.82	4.19	74.34	8.84	12.14	2.383	1.911	98.3	96.6	76.0	78.0	52.7	49.6
U.K.	8292	17630	9.26	22.06	16.26	62.99	7.59	10.41	1.982	1.758	98.5	94.4	70.4	74.6	39.8	53.8
U.S.	11379	26284	15.06	29.71	34.91 (29.06)[2]	65.43 (48.75)[2]	10.55	13.56	2.076	1.860	94.5	94.9	64.5	76.6	37.7	59.8
Average Annual Rates of Growth (percent p.a.)																
Canada	2.2		1.6		2.9		1.07		-0.2		0.01		0.5		1.7	
France	2.6		3.4		4.9		1.16		-0.6		-0.32		0.0		0.6	
W.Germany[1]	2.6		3.5		5.1		1.00		-0.6		-0.23		-0.1		0.2	
Italy	3.0		3.7		5.3		1.32		-0.4		-0.25		-0.1		0.2	
Japan	4.7		5.0		8.0		0.86		-0.5		-0.05		0.1		-0.2	
U.K.	2.2		2.5		3.8		0.86		-0.3		-0.11		0.2		0.8	
U.S.	2.3		1.9		1.7 (1.5)[2]		0.68		-0.3		0.01		0.5		1.2	

Notes:
1. Data for West Germany are only available through 1994.
2. Numbers in parentheses refer to net tangible capital stocks.

3. The Tests of Hypotheses

In order to verify the validity of the meta-production function approach and to identify the structure of the technology as well as the nature of the scale effects and technical progress, we 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 of course assign much lower 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. (In other words, the probability of our falsely rejecting any one or more of our tested hypotheses is one in ten.) The assigned levels of significance, test statistics and p-values for the different null hypotheses are presented in Tables 3.1, e.g., for the hypothesis of Hicks-neutrality of technical progress, 1% and for the hypothesis of purely labor-augmenting technical progress, 0.5%.

The Maintained Hypothesis of the Study

We first test the basic maintained hypothesis of our study, namely that the aggregate production functions of all seven countries are identical in terms of "efficiency-equivalent" inputs, that is, there is a single meta-production function and that technical progress can be represented in the commodity-augmentation form with each augmentation factor being a geometric function of time. This hypothesis cannot be rejected at our chosen level of significance. The non-rejection of the maintained hypothesis lends empirical support to the validity of the meta-production function approach adopted in this study.

Table 3.1: Tests of Hypotheses[1]

Tested Hypothesis	Maintained Hypothesis	Assigned Level of Significance	Number of Restrictions	Test Statistic χ^2/degrees of freedom	p-value
I. Maintained Hypotheses of the Meta-production Function Approach					
Single Meta- Production Function & Commodity Augmentation	Unrestricted	0.01	43	0.14	1.0000[2]
II. Traditionally Maintained Hypotheses					
(1a) Homogeneity	I	0.005	3	15.50	0.0000[2]
(1b) Constant Returns to Scale	I+II(1a)	0.005	1	0.78	0.3777
(2) Neutrality	I	0.01	42	1.91	0.0003
(3) Profit Maximization	I	0.01	35	2.51	0.0000[2]
III. Hypotheses on Intangible Inputs					
(1) No Human Capital Effect	I	0.01	4	9.12	0.0000[2]
(2) No Technical Progress	I	0.01	56	2.31	0.0000[2]
IV. Hypotheses on Augmentation Levels					
(1) Identical Augmentation Levels for Tangible Capital	I	0.005	6	1.19	0.3058
(2) Identical Augmentation Levels for Labor	I	0.005	6	2.06	0.0547
(3) Identical Augmentation Levels for Human Capital	I	0.005	6	1.32	0.2420
V. Hypotheses on Augmentation Rates					
(1) Purely Output-Augmenting[3]	I	0.01	42	1.91	0.0003
(2) Purely Tangible Capital-Augmenting	I	0.005	42	1.54	0.0142
(3) Purely Labor-Augmenting	I	0.005	42	2.30	0.0000[2]
(4) Purely Human Capital-Augmenting	I	0.005	42	1.48	0.0234
VI. Test of No Oil Price Effect (1974-1985)	I	0.01	28	1.95	0.0018

Notes:
[1]The variance-covariance matrix is updated successively at the non-identical production function and identical production function and commodity-augmentation stages and fixed thereafter.
[2]Due to rounding.
[3]The test for the hypothesis of purely output-augmenting technical progress is identical with the test for that of neutrality.

Traditional Maintained Hypotheses

Constant returns to scale, (Hicks-) neutrality of technical progress and profit maximization with competitive output and input markets are the three principal traditionally maintained hypotheses in the empirical measurement of total factor productivity (or equivalently technical progress). We test these three hypotheses in parallel, conditional on the maintained hypothesis of this study.

With human capital explicitly distinguished as a separate measured input, constant returns to scale in production can have two distinct meanings. First, one may say that there are constant returns to scale if doubling the quantities of tangible capital (in constant prices), labor (in hours), and human capital (in total number of school years of the working-age population) doubles real GDP. Alternatively, one may also say that there are constant returns to scale if doubling the quantities of tangible capital (in constant prices), labor (in hours), and human capital (in terms of the average number of school years per person of the working-age population) doubles real GDP. Constant returns of the first kind is conditioned on the average number of school years per person of the working-age population being held constant, assuming that the doubling of the labor hours comes from a doubling of the working age population of the same average education. Constant returns of the second kind imply that the average number of school years per person is also doubled (and hence human capital in terms of the total number of school years is increased four times). It should however be borne in mind that doubling the average number of school years requires a long time because of the long gestation period and durability of human capital. The hypothesis that we test in this study is constant returns of the second kind.

The hypothesis of constant returns to scale is further separated into the hypotheses of homogeneity and constant returns to scale.[15] The hypothesis of profit maximization is tested only with respect to labor and human capital combined because separate independent data on the costs of "pure" labor, that is, labor

[15]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.

unbundled from human capital, and human capital by itself, are not available. We find that all of these hypotheses can be separately rejected at their assigned levels of significance.[16]

Hypotheses on the Existence of Human Capital Effects and Technical Progress

Having established the validity of our approach, we proceed to test whether human capital has an effect on aggregate real output and whether there is any technical progress. Both hypotheses can be separately rejected at any level of significance. We conclude that both human capital and technical progress, as represented by the time trend variable, are important determinants of postwar aggregate real output in the G-7 countries.

Hypotheses on the Nature of Technical Progress

Next, we explore the nature of technical progress. We test whether: (1) augmentation level parameters are identical across countries; (2) technical progress can be represented as respectively purely output-augmenting, purely capital-augmenting, purely labor-augmenting and purely human capital-augmenting. The purpose of these tests is to establish the levels, rates and biases of technical progress, if any, as well as to obtain a parsimonious specification. Under the commodity-augmentation hypothesis and with one possible break in the trend of the commodity-augmentation factors due to the oil price shocks (as modeled in equation (2.6)), the number of independent parameters required to represent technical progress is 12 per country--four commodity-augmentation level and eight augmentation rate parameters. The interesting question is whether a smaller number will suffice.

We assign a level of significance of 0.015 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

[16]The hypothesis of profit maximization with respect to labor and human capital combined can be tested separately for each country. The values of the test-statistics, each of which has 4 degrees of freedom, are 3.60, 4.41, 9.95, 2.13, 3.23 for Canada, France, West Germany, Italy, Japan, the U.K. and the U.S. respectively. If the test of each country is assigned a level of significance equal to 0.0007 (so that their combined level of significance is no greater than 0.005) the hypothesis of profit maximization with respect to labor can be rejected only for Japan. However, non-rejection of this hypothesis is not sufficient to imply profit maximization because the a^*_{Lii}'s turn out to be very different from $(a^*_{Li} + a^*_{Hi})$'s. The test-statistic of the hypothesis that $a^*_{Lii} = (a^*_{Li} + a^*_{Hi})$, $\forall$ i has a value of 8.21 with 7 degrees of freedom, which can be rejected at any reasonable level of significance.

capital, labor, and human capital respectively. We find that we cannot reject the hypotheses of identical augmentation level parameters across countries at the assigned levels of significance. This implies that in the base year (1990), the "efficiencies" of capital, labor, and human capital were not significantly different across countries.[17] For the hypotheses of purely output, capital, labor or human capital-augmenting technical progress, we allocate 0.005 each for capital, labor, and human capital respectively (note that purely output-augmenting technical progress has exactly identical implications as Hicksian neutrality of technical progress, which has already been tested). We also find that we can reject the hypotheses of purely output-augmenting (Hicks-neutral) technical progress and purely labor-augmenting (Harrod-neutral) technical progress. However, we cannot reject the hypotheses of purely capital-augmenting (Solow-neutral) or purely human capital-augmenting technical progress.[18] In the next section we shall discuss in detail the implications of simultaneous purely capital- and human capital-augmenting technical progress.

Hypothesis on the Effects of the Oil Price Shocks

Finally, we test the hypothesis of no oil price effect. The hypothesis implies that the commodity-augmentation rates are constant throughout the period under study and do not change during the period of high oil prices, 1973-1985. The hypothesis can be decisively rejected. We conclude that there is indeed a statistically significant negative effect of oil price shocks on the rates of technical progress.[19]

4. Simultaneous Purely Capital- and Human Capital-Augmenting Technical Progress

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[17]However, 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,

[18] Either purely capital-augmenting or purely human capital-augmenting technical progress implies that the rates of labor augmentation are zero. 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.

[19] Recall that the estimated c_{iK}'s are the rates of augmentation of the gross fixed capital stock and are thus net of the implicit rates of depreciation. Thus, to the extent that the oil price shocks accelerated the depreciation of the capital stock, they would result in declines in the measured rates of capital augmentation.

It is somewhat surprising to find that technical progress can be represented simultaneously as purely capital-augmenting and purely human capital-augmenting rather than the more frequently assumed neutral or labor-augmenting variety. What are the implications of simultaneous purely capital-augmenting and purely human-capital augmenting technical progress? Purely capital-augmenting technical progress implies that the aggregate production function can be written in the form:

$$(4.1) \qquad Y = F(A_K(t)K, H, L).$$

Thus, the benefits of technical progress are higher the higher the level of the capital stock--capital and technical progress are complementary. A country with a low level of capital stock relative to labor and human capital will not benefit as much from technical progress as a country with a high level of capital relative to labor and human capital. Similarly, purely human capital-augmenting technical progress implies that the aggregate production function can be written in the form:

$$(4.2) \qquad Y = F(K, A_H(t)H, L),$$

with human capital and technical progress being complementary to each other.

It can be shown that the only aggregate production function that can be simultaneously written in the forms of equations (4.1) and (4.2) must take the form:

$$(4.3) \qquad Y = F(A(t)K^{\lambda}H^{1-\lambda}, L).$$

We shall refer to this form of technical progress as "generalized Solow-neutral" technical progress. Equation (4.3) implies that capital and human capital together form a composite capital input that is separable from labor, instead of the more customary assumption that human capital and labor form a composite labor input that is separable from capital. Thus, capital and human capital are complementary to each other and to technical progress. The complementarity between capital and human capital is also consistent with empirical findings at the microeconomic level of capital-skills complementarity (see Griliches (1962)).

Moreover, if technical progress cannot be expressed in the purely output-augmenting (Hicks-neutral) form, its empirical measurement, defined as the growth in real output holding measured inputs constant, cannot be simply cumulated over time, and depends on the evolution of the quantities of the other inputs—capital, labor and human capital.[20] In fact, by partially differentiating equation (4.3) with respect to t, we find that:

$$(4.4) \qquad \frac{\partial \ell n Y}{\partial t} = \frac{\partial \ell n F}{\partial \ell n K}(A(t)K^{\lambda}H^{1-\lambda}, L)\frac{\dot{A}(t)}{A(t)},$$

so that realized technical progress depends on the elasticity of output with respect to the composite capital consisting of measured capital and human capital, labor, as well as the rate of capital augmentation. In this study, the rate of capital augmentation, $\dot{A}(t) / A(t)$, is taken to be exogenous 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, human capital and time through the elasticity of output with respect to the quantity of composite capital, is endogenous.

The value of the elasticity of output with respect to measured composite capital, for given quantity of labor and time, for a monotonic and concave production function, always lies between zero and one. Moreover, holding labor and time constant, the elasticity can be either an increasing or a decreasing function of the quantity of capital. However, given that the rate of growth of capital is typically much higher than the rate of growth of labor in the industrialized countries, the output elasticity of capital is likely to be a decreasing function of the quantity of capital. Thus, as capital continues to accumulate physically and to be augmented technologically over time while the labor input grows slowly or not at all, the output elasticity of capital can be expected to fall. This implies that the rate of realized technical progress is likely to fall over time unless the rate of composite capital augmentation increases over time. Notice, however, it is the rate of growth of composite capital that matters, so that an acceleration of human capital accumulation will also

[20] See Hulten (2000), who also discusses several other issues in the measurement of productivity and

help. If, however, the rate of capital augmentation decreases over time, then the rate of realized technical progress will slow down. This may provide yet another plausible explanation for the apparent productivity slowdown.

The empirical results reported here also have significant implications for public policy. First, they reaffirm the importance of capital accumulation and technical progress as the most important sources of economic growth for the Group-of-Seven countries in the postwar period. Second, the results indicate that capital accumulation and technical progress are complementary, i.e., they amplify the effects of each other on productivity. This places additional emphasis on the importance of continual new investment.[21]

5. Empirical Estimates of the Aggregate Meta-Production Function

We synthesize the results of sections 3 and 4 and impose the restrictions implied by the hypotheses that are not rejected at the chosen levels of significance, namely: identical augmentation level parameters for tangible capital, labor and human capital; zero augmentation rate parameters for output and labor; and generalized Solow-neutrality (see equation (4.3)) on our estimation. The results are presented in Table 5.1.

The estimated capital augmentation rates, c_{iK}'s, are positive and statistically significant for all countries. Japan has the highest rate--16.6 percent per annum, followed by Italy (14.1 percent), West Germany (11.9 percent), France (11.3 percent), the United States (9.6 percent)[22] and the United Kingdom (7.8 percent). Canada has the lowest rate at 6.9 percent per annum. However, during the period 1973-1985, the capital augmentation rates of all countries declined. Canada, with its significant domestic energy resources, had a trivial decline of 0.2 percent. The United Kingdom (with its North Sea oil) and France (with its large nuclear power program) had the smallest declines of 0.6 and 0.9 percent respectively. Japan had the largest decline in the capital augmentation rate, from 16.6 percent to 8.0 percent, a full 8.6

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technical progress.

[21] This implication is similar to that of Delong and Summers (1991) who emphasize the importance of investment in equipment. However, capital-technology complementarity in itself does not necessarily imply embodiment of technical progress.

percentage points. However, even during this period, it remained true that the United States (6.9 percent), the United Kingdom (7.2 percent) and Canada (6.7 percent) still had the three lowest rates of capital augmentation among the G-7 countries.

Functions of Parameters of Interest

In Table 5.2 we present the estimated values of some parameters of the aggregate production function of interest for the G-7 countries in 1990. Our estimates of the production elasticities of tangible capital in 1990 range between 12.5 percent (West Germany) and 15.3 percent (Canada) and are significantly lower than what may be estimated from the traditional factor-share method under the assumptions of constant returns to scale and profit maximization with competitive markets. Our estimates of the production elasticities of human capital are about half as those for tangible capital--they range from 6.6 percent (West Germany) to 8.1 percent (Canada). The combined tangible and human capital elasticities range between 19.0 percent (West Germany) and 23.4 percent (Canada).

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[22] The estimated rate of capital augmentation for the U.S. when the gross capital stock is used also turned out to be 9.6 percent.

Table 5.1: Estimated Parameters of the Aggregate Production Function: Final Specification[1]

$$Y = F((A_{iK}(1+c_{iK})^{[(1-D_1(t-t_{73})+D_2(t-t_{85})]}(1+c_{iK}+c_{iK1})^{D_1(t-t_{73})-D_2(t-t_{85})}K)^{\lambda}H^{1-\lambda}, L)^{2,3}$$

Parameter	Value	t-ratio
a_K	0.324	(0.609)
$a_K \bullet \lambda$	0.212	(0.882)
$a_K \bullet (1-\lambda)$ $(=a_H)$	0.112	(0.384)
a_L	0.492	(0.960)
B_{KK}	-0.068	(-0.959)
B_{LL}	-0.058	(-0.678)
B_{KL}	0.070	(1.079)
c_{CK}	0.069	(2.199)
c_{FK}	0.113	(3.999)
c_{GK}	0.119	(4.572)
c_{IK}	0.141	(4.340)
c_{JK}	0.166	(4.187)
c_{UKK}	0.078	(3.684)
c_{USK}	0.096	(4.664)
c_{CK1}	-0.002	(-0.076)
c_{FK1}	-0.009	(-0.420)
c_{GK1}	-0.030	(-1.328)
c_{IK1}	-0.049	(-2.042)
c_{JK1}	-0.088	(-3.616)
c_{UKK1}	-0.006	(-0.289)
c_{USK1}	-0.027	(-1.257)
λ	0.654	(1.937)
R^2	0.805	
D.W.	1.933	

Notes: 1 The final specification is in first-differenced form.

2. D_1 is a dummy variable taking the value 1 for years 1973 and thereafter and 0 otherwise; D_2 is a dummy variable taking the value 1 for years 1985 and thereafter and 0 otherwise.

Table 5.2
Estimated Production Elasticities, Returns to Scale and Rates of Technical Progress
(at 1990 Values of the Variables)

	Tangible Capital Elasticity	Labor Elasticity	Human Capital Elasticity	Total Capital Elasticity[1]	Total Labor Elasticity[2]	Degree of Local Returns to Scale	Rate of Local Technical Progress	Actual Labor Share	Elasticity of Substitution Between Composite Capital and Labor
Canada	0.153	0.629	0.081	0.234	0.710	0.944	0.011	0.590	0.713
	(5.559)	(7.473)	(0.638)	(1.648)	(4.968)	(3.528)	(2.975)		(6.120)
France	0.130	0.672	0.069	0.200	0.742	0.942	0.015	0.615	0.692
	(6.481)	(9.319)	(0.660)	(1.804)	(5.138)	(3.863)	(5.933)		(5.678)
W. Germany	0.128	0.680	0.068	0.196	0.748	0.944	0.015	0.634	0.689
	(6.934)	(9.698)	(0.667)	(1.867)	(5.100)	(3.896)	(7.107)		(5.580)
Italy	0.125	0.682	0.066	0.190	0.748	0.938	0.018	0.637	0.684
	(6.358)	(9.233)	(0.655)	(1.768)	(5.258)	(3.937)	(7.193)		(5.632)
Japan	0.138	0.679	0.073	0.211	0.752	0.963	0.023	0.615	0.701
	(5.732)	(7.688)	(0.659)	(1.786)	(4.522)	(3.559)	(7.359)		(6.077)
U.K.	0.149	0.646	0.079	0.228	0.725	0.954	0.012	0.658	0.711
	(6.611)	(10.581)	(0.645)	(1.710)	(5.083)	(3.580)	(6.112)		(6.200)
U.S.	0.150	0.667	0.079	0.230	0.746	0.976	0.014	0.648	0.714
	(5.531)	(5.619)	(0.690)	(2.024)	(3.785)	(3.336)	(5.118)		(5.804)

Notes: Numbers in parentheses are t-ratios.
[1] Total capital elasticity is the sum of tangible capital and human capital elasticities.
[2] Total labor elasticity is the sum of the labor and human capital elasticities.

Our estimates of the production elasticities of labor in 1990 lie within a relatively narrow band between 62.9 percent (Canada) and 68.2 percent (Italy). Superficially, they are quite comparable in value to labor elasticities estimated from the factor share method. However, if we consider the share of total labor costs in total output as reflective of the combined compensation to both tangible labor and human capital, then it should be equal to the sum of the tangible labor and human capital elasticities, i.e., the total labor elasticities; but the estimated total labor elasticities for 1990 are all higher than the actual shares of labor costs in total output by approximately 10 percentage points. The gap is the lowest for the United Kingdom, at 6.7 percent. This finding suggests that labor and human capital combined may possibly be paid less than their marginal products and tangible capital may appear to be paid more than its marginal product because of its status as the residual claimant to output.[23]

We have previously rejected the hypotheses of homogeneity and constant returns to scale in production in all inputs, tangible capital, human capital, and labor. This implies that the degree of returns to scale not only is not unity but also depends on the quantities of capital, human capital and labor. The degree of local returns to scale for the ith country is defined as the proportional increase in output in response to an infinitesimal proportional increase in all inputs (tangible capital, labor, and human capital measured as the average number of years of education per person in the working age population), that is, constant returns of the second kind, and may be computed as:

$$\mu_i(K,L,H,t) = \frac{\partial \ell n F}{\partial \ell n \pi}((1+c_{iK})^t(\pi K)^{\lambda}(\pi^2 H)^{1-\lambda},\pi L)|_{\pi=1}$$

At the 1990 values of the independent variables of each country, however, the estimated degree of local returns to scale is very close to and not statistically significantly different from, unity.[24]

[23] The "excess" return to tangible capital may actually be a return to investment in forms of intangible capital, such as R&D, which are not captured by our measurement of capital.

[24] The t-ratios for the null hypothesis that the degree of local returns to scale was equal to unity in 1990, that is, the null hypothesis of locally constant returns to scale, are 0.411 for Canada, 0.257 for France, 0.190 for West Germany, 0.234 for Italy, 0.151 for Japan, 0.307 for the United Kingdom and 0.078 for the United States. The critical values are 2.58, 2.81 and 3.29 for levels of significance equal to 0.01, 0.005 and 0.001 respectively.

We have also previously rejected the hypothesis of neutrality of technical progress. This implies that the rate of technical progress depends on the quantities of capital, human capital and labor. The rate of local technical progress may be defined as the proportional increase in output in response to an infinitesimal increase in time, holding all inputs constant. The rate of local technical progress realized may be computed as:

$$\tau_i(K, L, t) = \frac{\partial \ell nF}{\partial t}((1 + c_{iK})^t K^\lambda H^{1-\lambda}, L)$$

$$= \frac{\partial \ell nF}{\partial \ell nK^\#}((1 + c_{iK})^t K^\lambda H^{1-\lambda}, L) \ln(1 + c_{iK}),$$

where $K^\#$ is the quantity of composite capital, $K^\lambda H^{1-\lambda}$. Thus, the rate of local technical progress is equal to the product of the production elasticity of composite capital and $\ln(1+c_{iK})$, which is approximately equal to c_{iK}, the rate of capital augmentation, for typical values of c_{iK}. If the rate of capital augmentation is unchanged, then the rate of local technical progress declines with the level of composite 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, labor, and human capital, and to that extent may be regarded as endogenous.[25]

Is Technical Progress Capital-Saving or Labor-Saving?

One important question is whether technical progress is labor-saving, in the sense that the (cost-minimizing) demand for labor relative to capital, at given quantity of output and prices of capital and labor, is reduced as a result of the technical progress. In the two-input case, it can be 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 our case, even though we distinguish three inputs explicitly, we have effectively two inputs, because tangible capital and human capital have been found to be separable from labor and together form a composite capital. Moreover, technical progress has been found to be

[25] This notion of "endogenous technical progress" is different from but sympathetic to the "endogenous technological change" of Romer (1990).

generalized Solow-neutral, that is, composite capital-augmenting. In Table 5.2, the estimated values of the elasticities of substitution between composite capital and labor in 1990 are presented. They range within a narrow band between 0.68 and 0.71 in absolute value, indicating relatively modest substitutability between composite capital and labor. This finding in turn implies 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, as opposed to transitory, unemployment in the aggregate economy is unlikely to be technologically induced. Instead, new technology makes a given quantity of capital, tangible or human, go further as a complementary input to labor.

6. The Sources of Economic Growth

Using our estimates of the meta-production function, we derive estimates of the average annual rate of technical progress in each of the G-7 countries. Our estimates of the average annual rates of technical progress are calculated as the geometric mean of the logarithmic average difference in output over the relevant period, holding inputs at the initial and terminal values respectively.

In Table 6.1, we present our estimates of the average annual rates of technical progress (or equivalently rates of growth of total factor productivity). For the postwar period as a whole, Japan had the highest average annual rate of technical progress, 3.7%, followed by the three Western European countries of France, W. Germany and Italy, at approximately 2.5%. The average annual rate of technical progress of the United States was 2.0%. The United Kingdom and Canada trailed with 1.5% and 1.3% respectively.

In this case of three inputs, it is not possible to use the traditional growth accounting formula to estimate the average annual rates of technical progress without additional assumptions on the relationship between the marginal productivities of the labor input and the human capital input. Instead, we obtain an alternative set of estimates of technical progress by imposing the restriction of constant returns to scale in the three inputs—capital, labor, and human capital—an assumption that is usually maintained in traditional growth accounting exercises. These restricted estimates are also presented in Table 6.1 for comparison.

The restricted estimates of average annual technical progress are not appreciably different from the unrestricted estimates, consistent with our finding that the degree of local returns to scale in these countries and over this period is not significantly different from unity.

In Table 6.2, we present our estimates of the relative contributions of the different sources of growth for each of the seven countries, using our restricted estimates of the aggregate meta-production functions. Our estimates of the average annual contributions of capital, human capital and labor are computed analogously to that for technical progress.

Table 6.1: Estimated Average Annual Rates of Technical Progress (percent p. a.)

Country	Period	Entire Period	First Period (~1973)	Second Period (1973~)
Canada	58-97	1.3	1.5	1.1
France	58-97	2.3	2.9	1.8
W. Germany	58-94	2.4	3.0	1.9
Italy	60-97	2.7	3.5	2.1
Japan	58-97	3.7	4.9	2.7
U.K.	58-97	1.5	1.8	1.3
U.S.	50-98	2.0	2.3	1.5

Table 6.2
Relative Contributions of the Sources of Growth (percent)

	Physical Capital	Labor	Human Capital	Oil Price Effect	Technical Progress
Entire Period					
Canada	25	31	8	0	36
France	29	-3	6	-2	69
W. Germany	29	-5	5	-6	77
Italy	27	-5	6	-9	82
Japan	33	6	4	-11	68
U.K.	31	1	5	-1	65
U.S.	17	23	6	-4	58
First Period	**(~1973)**				
Canada	26	31	9	0	34
France	34	3	6	0	57
W. Germany	35	0	3	0	62
Italy	32	-6	5	0	69
Japan	38	4	5	0	54
U.K.	37	4	3	0	55
U.S.	21	16	7	0	56
Second Period	**(1973~)**				
Canada	25	30	7	0	38
France	26	-14	7	-3	85
W. Germany	24	-17	7	-14	99
Italy	23	-4	6	-16	90
Japan	29	8	4	-21	80
U.K.	26	-3	6	-3	74
U.S.	13	34	5	-8	56

We find that over the entire period under study, technical progress is the most important source of economic growth for all countries except Canada. With the exception of Canada, where it accounts for only 36 percent of economic growth, technical progress accounts for at least one half of the economic growth in the G-7 countries.[26] Second most important is the growth of tangible capital, which accounts for between roughly a fifth and a third of economic growth. The increase in human capital, which accounts for a little less than 10 percent of the economic growth in the G-7 countries, is the third most important source of economic growth for all but Canada, Japan and the United States, where the growth of labor is the third most important source. Labor input growth accounts for no more than 6 percent (and in fact has a negative contribution in France, West Germany and Italy), except for Canada and the United States, where it accounts for between 20 percent and one-third. The relative importance of the growth of labor in Canada and the United States stands in marked contrast to the other major industrialized countries. Significant immigration, the rise in the female labor force participation, and the surge in the working age population from the baby boom generation in these two countries are the major causes. The oil price shock had a negative effect on economic growth of approximately 10 percent over this period for Italy and Japan and 6 percent for West Germany, and essentially zero for the oil producing countries of Canada, the United Kingdom and the United States, and for France where there is significant use of nuclear energy.[27]

Separating the postwar period into two sub-periods, pre- and post- oil price shock (1973), does not alter appreciably our empirical findings in a qualitative sense. Technical progress remains the most important source of economic growth for all countries except Canada in both sub-periods. However, it accounts for a much greater proportion of the slower economic growth in the second sub-period than the first. Capital formation remains the second most important source of economic growth for all countries except Canada and the United States in the second sub-period, where the sizable labor input growth is the second most important source. For the European countries, the quantities of labor input have all been

[26] The result that technical progress, or the growth of total factor productivity, has been the most important source of the growth of real output is reminiscent of the findings of Kuznets (1971) for an earlier period (see pp. 51-98, especially Tables 9 and 11).

declining in the second sub-period, and thus responsible for significant negative contributions to growth there. Of course, the oil price shock has no effect on economic growth in the pre-oil price shock sub-period. But it has a large negative effect of 15-20 percent in the post-oil price shock sub-period in West Germany, Italy and Japan.

We note that tangible capital formation and technical progress combined essentially account for 100 percent of the economic growth of France, West Germany, Italy, Japan and the United Kingdom. In Canada and the United States, where the labor input and to a lesser extent the human capital input grew more rapidly than in other countries during this period, capital and technology combined still account for 61 and 75 percent of the economic growth, respectively (69 and 81 percent if human capital is included).

7. The Sources of the Growth Slowdown

It is evident that the measured rate of economic growth of each of the G-7 countries, except Canada, is lower in the sub-period after 1973 (post oil-price shocks) compared to the sub-period before (see Table 1.1), despite the recent increase in the U. S.[28] The slowdown in the growth rate ranges from 1.1 percentage points in the U. K. and the U.S. to 6.0 percentage points in Japan. As a proportion of the growth rate in the first period, the slowdown represents about one-third for Canada, the U.K. and the U.S. and well over half for the non-oil producing G-7 countries. The interesting question is: What were the sources of this growth slowdown?

Just as we can perform a "sources of growth" accounting exercise, we can do likewise for the sources of the growth slowdown to ascertain its proximate causes. That is, we decompose the slowdown to determine the extent to which it was caused by slower growth of the inputs of capital, labor and human capital; changes in the responsiveness of output to the growth of inputs (due, for example, to capital

[27] We turn next to the pre-and post-oil shock periods separately.

[28] While economic growth has picked up for the last three years in the U. S. alone among the G-7 countries, whether this foreshadows a higher rate of aggregate productivity growth remains a source of controversy (see Gordon (2000) and Jorgenson and Stiroh (2000)).

deepening); changes in the rate of capital augmentation and more generally slower technical progress; and the effects of the oil price shocks themselves.

The results of the decomposition are presented in Table 7.1. Generally, the three most important sources of the growth slowdown are the slower rates of capital-augmenting technical progress; slower rates of capital formation; and an apparent reduced responsiveness of output with respect to capital input growth. The slower rate of local technical progress accounts for between 31% (Canada) and 53% (the U.S.) of the growth slowdown. The lower rate of capital formation accounts for between 6% (Canada) and 31% (U.K.), with 24% for the U.S. The reduced elasticity of output with respect to capital accounts for 16% (W. Germany) to 23% (Canada), with 19% for the U.S.[29]

Factors especially important for particular countries, as opposed to uniformly important in explaining the growth slowdown, include: the oil price shocks, accounting for between 11 and 17 percent in W. Germany, Italy, Japan and the U.S.; and slower labor input growth accounting for 39% in Canada, 13 percent in France, and 9 percent in West Germany.

[29] For an alternative explanation of the slowdown, see Romer (1987).

Table 7.1 Sources of Growth Slowdown (decomposition in percent)

	Slowdown in Growth Rate[1] (percentage points)	Due to the Change in Elasticity of Output with respect to :			Due to the Change in Growth Rate of :			dy/dxoil	Local Technical Progress
		Tangible Capital	Labor	Human Capital	Tangible Capital	Labor	Human Capital		
Canada	1.8	23.0	-15.5	7.1	6.2	38.6	8.9	1.1	30.7
France	2.9	18.6	0.4	3.8	19.5	12.9	1.2	2.8	40.9
W.Germany	2.5	16.0	1.0	2.5	25.6	8.6	-1.7	10.5	37.6
Italy	2.8	18.3	1.7	3.2	22.6	-7.4	-0.2	14.7	46.9
Japan	6.0	20.8	-2.2	2.5	21.0	3.5	2.9	15.0	36.5
U.K.	1.1	20.7	-1.0	2.9	31.4	5.0	-2.2	3.9	39.3
U.S.	1.1	18.6	-12.6	5.9	24.1	-10.8	4.8	17.2	52.8

Note: 1. Growth rate difference between first period (~1973) and second (1973~).

8. Concluding Remarks

We have implemented a new method of analyzing technical progress and economic growth based on the concept of an aggregate meta-production function, using updated and improved pooled time series data from the Group-of-Seven countries for the post-war period. We have also explicitly introduced human capital as a factor of production, in addition to tangible capital and labor. We find technical progress to be generalized Solow-neutral and that capital, human capital, and technical progress are complementary to one another.[30]

With our new approach, we have obtained alternative estimates of the rates of technical progress as well as alternative decompositions of economic growth into its sources—tangible capital, labor, human capital and technical progress—that are independent of the conventional assumptions.[31] We have found that technical progress is by far the most important source of economic growth of the G-7 countries except Canada, accounting for more than 50 percent, in contrast to the growth accounting studies of Denison (1962, 1967, 1979) and Griliches and Jorgenson (1966, 1967). Jorgenson, Gollop and Fraumeni (1987) and Dougherty and Jorgenson (1996).[32] Further, technical progress is found to be capital, not labor, saving and thus not a cause of structural unemployment.

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 in which, as in this study, no quality adjustments are made to the inputs, they are, in fact, quite different on at least three counts. First, in addition to tangible capital, human capital has been explicitly introduced and recognized as a factor of production. Second, the early

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[30]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.

[31] For example, the traditional formula for cumulating technical progress through time is not valid if technical progress is not (Hicks-) neutral or, equivalently, purely output-augmenting.

[32] We have not made explicit adjustments for the quality of capital or labor, as were done by Denison (1962, 1967, 1979) and Jorgenson, Gollop and Fraumeni (1987). Instead, we allow any trend of improving input quality to be captured by the inclusion of the human capital stock variable and by the rates of factor augmentation themselves . Thus, what we attribute to technical progress may include what others attribute to the improvement in the qualities of the inputs.

studies typically assume constant returns to scale, neutrality of technical progress, and profit maximization with competitive markets. These assumptions were not maintained in this study.[33] Third, 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 tangible and human capital stock much less good than a country with a high level. This is one explanation for the slow pace of convergence. 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. This capital-technology complementarity, which implies a positive interactive effect of capital and technical progress, distinguishes our results from others.

At the aggregate level, one implication of capital-augmenting technical progress is the importance of capital, tangible as well as human, to economic growth. For a given rate of capital augmentation, the benefits of technical progress to the economy are directly proportional to the size of the composite capital stock. An increase in the national 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 composite capital and labor is less than unity, is that technical progress is (composite) capital-saving rather than labor-saving, in the sense that the desired tangible and human capital-labor ratios for given prices of tangible capital, human capital and labor, and quantity of output, declines with technical progress. Capital-augmenting technical progress is thus unlikely to cause structural unemployment through the technological displacement of workers; in fact, the opposite is likely to be true.

[33] However, even if the hypothesis of constant returns to scale in production were maintained, the estimate of technical progress, and hence its contribution to economic growth, would have been virtually unchanged. These results are available upon request from the authors.

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