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Productivity convergence and economic growth: A frontier production function approach

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Productivity Convergence and Economic Growth: A Frontier Production Function Approach

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Productivity Convergence and Economic Growth: A Frontier Production Function Approach

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Abstract

The empirical growth literature has focused on capital accumulation but largely ignored productivity growth. To address this imbalance, we propose a methodology for analyzing productivity convergence based on frontier production functions. We examine whether departures from the frontier are cointegrated, determine the extent and speed of catch–up, and assess the importance of efficiency changes for economic growth. Using a sample of 26 OECD countries from 1965–90, we find convergence and catch–up is fairly strong among EU countries but not among the G–7. Overall, the ability to absorb new technology is an important source of economic growth.

Key Words: cointegration, convergence, growth, productivity, unit root
JEL Classification: C2, O47, O57

1 Introduction

In the last ten years, the empirical growth literature has rapidly expanded. The most prominent feature of this literature has been its focus on the question of convergence—do poorer countries grow faster than richer countries, thereby narrowing the income gap—a fundamental implication of the neoclassical growth model introduced by Solow (1956). While support for the convergence hypothesis is found in a number of recent papers (for example, Abramovitz (1986, 1990), Baumol (1986), Barro (1991, 1996), Barro and Sala-i-Martin (1991, 1992), Mankiw, Romer, and Weil (1992) and Islam (1995)), the empirics typically focus narrowly on the role of capital in generating economic growth. This is surprising given the important role of technology in endogenous growth models, e.g., Romer (1986, 1990).

Clearly, to the extent that differences in growth rates across countries arise from differences in productivity, the current literature provides an incomplete picture of cross–country growth patterns. Recent papers by Dowrick and Nguyen (1989) and Bernard and Jones (1996a,b,c) have attempted to fill this gap. Dowrick and Nguyen find that income levels of OECD countries have not converged since 1950. Despite this result, they find productivity catch–up to be a dominant and stable trend during the post–war period. Bernard and Jones argue that the adoption and accumulation of technologies is important for convergence. Thus, steady state levels of per capita output depend on countries' abilities to adopt new technologies. In a sense, countries that are good adopters benefit from inventions abroad, and this ability places them in a good position relative to all other countries. The authors emphasize their argument by pointing to empirical evidence that supports the hypothesis of technological differences across countries.

In this paper, we propose a methodology for examining productivity differences across countries. Our approach is based on a *frontier production function*, which is the empirical analog to the theoretical construct of the boundary of the production set. The advantage to focusing on maximum output is the ability to identify inefficiencies in production through observed departures from the frontier. Further, to the extent such inefficiencies reflect sluggish adoption of new technologies, improvements therein represent productivity catch–up from technology diffusion. However, with the exception of Färe et al. (1994), the empirical growth literature has largely ignored empirical techniques directed at the production frontier.

Our methodology proceeds in four steps. First, we construct an empirical representation of the frontier technology for a given set of countries. This can be accomplished through non–parametric programming methods or parametric econometric estimation techniques. Departures from the constructed frontier are translated into a measure of a country's efficiency, which we interpret as a country's ability to absorb technological innovations. Second, we determine whether the country-level efficiencies are cointegrated. Failure to reject the cointegration null for a set of countries would indicate a long–run relationship in the diffusion of technology within that set.[1] Third, we estimate convergence regressions to determine the degree of productivity convergence or catch–up in the cointegrated set. Finally, we assess the contribution of efficiency changes for economic growth.

We apply this methodology to a sample of 26 OECD countries observed over the period 1965–90, with two sets of questions in mind. Is there a long–run relationship between the country–level efficiencies, and if so, do they converge? In addition, is it justified to view capital accumulation as the sole driving force of output growth (in this sample)?

To summarize, we find fairly strong evidence of convergence among EU countries, but no significant long–run relationship among the G–7. Overall, our results suggest that the ability to absorb new technology innovations to be an important source of economic growth in the OECD.

This paper proceeds as follows. Section 2 describes the computation of productivity growth. In section 3, we develop our methodology for examining productivity convergence. Section 4 contains empirical results and section 5 concludes.

2 Measuring Productivity Growth

When we refer to the term "productivity," it is total factor productivity (TFP) rather than labor productivity that we have in mind. In the simple setup discussed below, the concept of TFP assumes that capital and labor are the only factors of production. We will look at two different ways to measure TFP growth. The distinction between these two approaches that is important for our purposes lies in the way the frontier concept is treated.

Consider the constant returns to scale version of a Cobb–Douglas production function $Y(t) = A(t)K(t)^{\alpha}L(t)^{1-\alpha}$, with Hicks–neutral productivity index $A(t)$. Taking derivatives with respect to time and rewriting the ensuing expression in percentage terms yields

$$\dot{A}/A \quad = \quad \dot{Y}/Y - \alpha\,\dot{K}/K - (1-\alpha)\dot{L}/L. \tag{1}$$

Productivity growth is defined as a residual, obtained as the difference between output growth and share–weighted input growth. In this formulation, observed output is assumed to be frontier

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[1] Similar strategies have been applied to international output series; see e.g., Bernard and Durlauf (1995)).

output, that is, all countries have access to and employ best–practice technology. Thus, since there are no movements toward or away from the "frontier," productivity growth is identified with shifts in the production function, i.e., technical change (cf. Solow (1957)).

The second approach explicitly incorporates the idea of the production frontier. Not every country is assumed to produce frontier level output. Deviations from the frontier reflect technical inefficiency; that is, a failure to produce the maximum possible output given inputs and the available technology. Thus, a productivity growth measure that allows for departures from the frontier can distinguish laggards from best–practice. Such a measure can also distinguish movements toward the frontier from movements of the frontier. The latter is the familiar concept of technical change, while the former is a measure of catch–up ignored in conventional growth empirics. As suggested by Färe et al. (1994), catch–up as represented by changes in a country's efficiency level is expected to capture technological diffusion.

Typically, efficiency levels are computed using either data envelopment analysis (DEA) or stochastic frontier analysis (SFA). DEA is a mathematical programming technique that does not require a functional form assumption, but also does not account for statistical noise, so that all departures from the frontier are counted as inefficiency. The alternative—estimating a parametric stochastic frontier—may be less robust in terms of functional form assumptions, but has the advantage of incorporating purely random deviations from the frontier in the form a regression disturbance. Moreover, SFA permits inference about features of technology like returns to scale. We employ both techniques, with one serving as a check on the deficiencies of the other.

3 Testing for Productivity Convergence

Our approach to productivity convergence is based on the idea that country–level efficiencies exhibit a long–run relationship. If so, measured efficiencies should be cointegrated. Then, among countries with cointegrated efficiency series, laggards may catch up or converge to the frontier, ostensibly through technological diffusion.

First, we obtain country efficiency levels from both DEA and SFA. The second stage of our analysis involves the application of unit–root tests to the efficiency series of each country. Third, we test whether there are any cointegrating relationships among the efficiency series. In the last stage, we estimate convergence regressions to determine the degree of catch–up. Furthermore, we evaluate the effect of efficiency change on output growth.[2]

3.1 Construction of Efficiency Series using DEA

To compute country–level efficiencies using DEA, we solve the following linear program:

$$\begin{array}{lrcll} \left(D_t(x_t^i, y_t^i)\right)^{-1} & = \max\limits_{\lambda,z} \lambda & & & \\ \text{s.t.} & \lambda y_{it}^k & \leq & \sum\limits_{i=1}^{N} z_i y_{it}^k, & k = 1, 2, \ldots, K, \\ & \sum\limits_{i=1}^{N} z_i x_{it}^l & \leq & x_{it}^l, & l = 1, 2, \ldots, L, \\ & z_i & \geq & 0, & i = 1, 2, \ldots, N, \end{array} \tag{2}$$

where $D_t(\cdot,\cdot)$ is an output distance function, y_{it}^k denotes output k of country i in period t, x_{it}^l, denotes input l of country i in period t, and the vector z contains intensity variables. As pointed out in Färe et al. (1994), the inverse of the output distance function is the Farrell (1957) output measure of technical efficiency.

3.2 Construction of Efficiency Series using SFA

In this case, we follow the usual procedures in the stochastic frontier literature introduced by Aigner, Lovell, and Schmidt (1977). The fundamental distinction between DEA and SFA is that the programming approach assumes a deterministic production frontier so that every deviation from it is interpreted as inefficiency. Hence, this approach does not account for noise in the data and thus does not allow statistical inference.

The stochastic frontier approach, on the other hand, specifically treats the frontier as random. Deviations from the frontier no longer represent just inefficiency but also statistical noise. The latter might be measurement error as well as circumstances that cannot be anticipated and are beyond the control of each country, such as climate or natural disasters. These random occurrences allow countries to deviate from the frontier and still be labeled efficient. More specifically, the stochastic frontier may be written as

$$y_i = f(\boldsymbol{x}_i; \boldsymbol{\beta}) \exp(v_i + u_i) \tag{3}$$

where y_i denotes output, $\boldsymbol{x}_i$ is a vector of inputs, and v and u are random variables. We assume the v_i are distributed iid normal with zero mean and constant variance σ_v^2 and represent random noise.

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[2] A similar approach was employed by Alam and Sickles (1998) to examine productivity convergence in the US airline industry.

The u_i are one–sided disturbances ($u_i \leq 0,\ \forall i$) with mean $\mu < 0$ and variance σ_u^2 and capture the inefficiency of each country.

To estimate the stochastic frontier model, one has to assume a specific functional form. In this paper, we will estimate a translog stochastic frontier model because it is a flexible functional form and imposes no a priori restrictions on the elasticities of substitution. The empirical production frontier can be expressed as follows:

$$\ln y_i = \beta_0 + \sum_{l=1}^{L} \beta_l \ln x_{il} + \frac{1}{2} \sum_{l=1}^{L} \sum_{m=1}^{L} \beta_{lm} \ln x_{il} \ln x_{im} + v_i + u_i, \tag{4}$$

with the symmetry restrictions $\beta_{lm} = \beta_{ml},\ \forall m, l,\ m \neq l$ imposed.

We estimate equation (4) by OLS separately for each year. Year–by–year regressions allow the greatest temporal flexibility in the production frontier parameters and parallel closely DEA which constructs a separate frontier for each year. The alternative of pooling the data and imposing some degree of parameter homogeneity is inappropriate in our sample, where $T = 26$.

OLS provides consistent estimates of all of the production frontier coefficients except the intercept term. With distributional assumptions for the v_i and u_i, the OLS estimate of the intercept can be corrected by a consistent estimate of $E(u_i)$, which is identified through the higher-order moments of the OLS residuals. The standard assumptions are that the v_i are normal and the one-sided u_i are half-normal.[3]

More importantly, the distributional assumptions allow estimates of the country-level inefficiencies to be extracted from the composed disturbance. Following Jondrow et al. (1982), this involves estimating the conditional expectation

$$E(u_i|\epsilon_i) = \mu_* + \sigma_* \frac{\phi(-\mu_*/\sigma_*)}{1 - \Phi(-\mu_*/\sigma_*)} \tag{5}$$

where $\epsilon_i = v_i + u_i$, ϕ and Φ represent the standard normal pdf and cdf, $\sigma^2 = \sigma_u^2 + \sigma_v^2$, $\mu_* = -\frac{\sigma_u^2 \epsilon_i}{\sigma^2}$, and $\sigma_*^2 = \frac{\sigma_u^2 \sigma_v^2}{\sigma^2}$. The level of technical efficiency (TE$_i$) is then obtained as the antilog of the conditional expectation of the one–sided error, i.e.,

$$\mathrm{TE}_i = \exp(-E(u_i|\epsilon_i)). \tag{6}$$

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[3] ML might be preferred on the grounds that it produces more efficient estimates of the βs, but the Monte Carlo results of Olson, Schmidt, and Waldman (1980) suggest that ML and "corrected" OLS perform equally well under the standard distributional assumptions.

3.3 Unit–Root Tests

After having constructed the two technical efficiency series for each country, the second step of our analysis consists of conducting unit–root tests. The unit–root inference is the basis for subsequent cointegration tests of long–run relationships between integrated series.

The interpretation of unit–root tests in this context is somewhat problematic. Recall that the DEA efficiency levels are bounded by zero and unity. Hence, they can never really diverge to infinity, which is what the presence of a unit root would suggest. In addition, unit roots represent a "razor's edge" problem. Nevertheless, failure to reject the unit–root null hypothesis can be interpreted as an indication of "persistence." In this view, the efficiency series can be treated "as if" they are I(1).

The simplest and most widely used test for unit–root nonstationarity is the Dickey–Fuller (DF) (1979) test. Depending on the assumptions about the data–generating process of the efficiency levels, several different test regressions are available. In section 4, we report results from the regression

$$\Delta \mathrm{TE}_{it} \quad = \quad (\alpha - 1)\mathrm{TE}_{i,t-1} + \omega_{it}, \tag{7}$$

where TE denotes the efficiency level series and ω_{it} is white noise. The usual DF test statistic is just the t–ratio corresponding to the coefficient of $\mathrm{TE}_{i,t-1}$.[4]

Since DF tests are characterized by low power in distinguishing roots that are close (and even not so close) to unity from ones that are exactly unity, we also perform the unit–root test proposed by Kwiatkowski, Phillips, Schmidt, and Shin (KPSS) (1992), which contrasts the stationarity null with a unit–root alternative. Stationarity can mean either level or trend stationarity, which can be tested for separately. Testing for level stationarity requires the residuals from a regression of the efficiency levels on a constant. Testing for trend stationarity requires the residuals, e_t, from a regression of the efficiency levels on a constant and a time trend. Assuming that the errors in these auxiliary regressions are iid,[5] the test statistic is constructed as

$$\mathrm{LM} \quad = \quad \frac{1}{T^2}\sum_{t=1}^{T} S_t^2/\hat{\sigma}_\epsilon^2 \tag{8}$$

where $S_t = \sum_{t=1}^{T} e_t, t = 1, \ldots, T$ and $\hat{\sigma}_\epsilon^2 = \frac{1}{T}\sum_{t=1}^{T}(e_t - \bar{e})^2$.

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[4] Test outcomes are not altered by the inclusion of drift and trend terms, nor by allowing for first-order dependence in the ω_{it}.

[5] If the iid assumption about the errors is dropped, the estimator of the variance is replaced by a consistent estimator of the long–run variance. This is the version of the test we employ.

3.4 Cointegration Tests

If a linear combination of two or more nonstationary series is stationary, then these series are said to be cointegrated. This means that even though each series diverges from its mean as time passes, the series move together in the long run. Therefore, cointegration between economic time series is often interpreted as indicating some sort of long–run equilibrium relationship.

We conduct two distinct cointegration tests: the Engle–Granger (1987) test and the Johansen (1991) test. We employ the former because its simplicity permits straightforward tests for cointegrating relationships between all country pairs. The latter has the advantage of being invariant to normalization and can reveal cointegrating relationships between more than two variables. However, because of data limitations, the Johansen test is infeasible for the entire sample of countries. We therefore apply this test to two subsets of countries: the G–7 and EU.

To implement the Engle–Granger test, we first regress the efficiency series of country i on that of country j:[6]

$$\mathrm{TE}_{it} = \beta_0 + \eta \mathrm{TE}_{jt} + v_t, \tag{9}$$

where v_t is a random disturbance. These two efficiency series can be regarded as cointegrated if the residuals from (9) are stationary. Thus, the null of no cointegration is tested by determining whether the $\hat{v}_t$ have a unit root, which involves estimating the test regression,

$$\Delta \hat{v}_t = (\alpha - 1)\hat{v}_{t-1} + \epsilon_t, \tag{10}$$

and applying a residual–based unit–root test.

In contrast, Johansen's test takes a full-information maximum likelihood (FIML) approach to the problem. Following Johansen, we specify a VAR in the country efficiency series (either G–7 or EU as noted earlier), which we express in levels as

$$\mathbf{TE}_t = \boldsymbol{\pi}_0 + \boldsymbol{\pi}_1 \mathbf{TE}_{t-1} + \boldsymbol{\pi}_2 \mathbf{TE}_{t-2} + \boldsymbol{\epsilon}_t, \tag{11}$$

where $\mathbf{TE}_t$ is a vector containing the period t efficiency level for each country and $\boldsymbol{\epsilon}_t$ is a zero-mean random vector with $E(\boldsymbol{\epsilon}_t\ \boldsymbol{\epsilon}'_s) = \boldsymbol{\Omega}$, $\forall t = s$ and zero, otherwise.[7] More convenient is the formulation in differences:

$$\boldsymbol{\Delta}\mathbf{TE}_t = \boldsymbol{\pi}_0 + \boldsymbol{\xi}_1 \boldsymbol{\Delta}\mathbf{TE}_{t-1} + \boldsymbol{\xi}_0 \mathbf{TE}_{t-1} + \boldsymbol{\epsilon}_t \tag{12}$$

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[6] Including a time trend had no impact on the results.

[7] We found a lag length of 2 was sufficient to capture the system dynamics.

where $\boldsymbol{\xi}_1 = -\boldsymbol{\pi}_2$ and $\boldsymbol{\xi}_0 = \boldsymbol{\pi}_1 + \boldsymbol{\pi}_2 - \boldsymbol{I}$ determines the extent to which the system is cointegrated.

To construct the test statistic, we estimate two sets of auxiliary regressions,

$$\begin{aligned} \Delta\mathrm{TE}_{it} &= \Pi_0 + \mathbf{\Pi}_1 \mathbf{\Delta TE}_{t-1} + u_{it}, && (13) \\ \mathrm{TE}_{i,t-1} &= \Theta_0 + \mathbf{\Theta}_1 \mathbf{\Delta TE}_{t-1} + v_{it}, && (14) \end{aligned}$$

for each country separately by OLS. These regressions serve to concentrate the likelihood function about $\boldsymbol{\xi}_0$ and $\mathbf{\Omega}$. The concentrated likelihood depends on the canonical correlations between u_t and v_t, which we calculate from the eigenvalues ($\hat{\lambda}_1 > \hat{\lambda}_2 > \cdots > \hat{\lambda}_n$) of

$$\hat{\mathbf{\Sigma}}_{vv}^{-1} \hat{\mathbf{\Sigma}}_{vu} \hat{\mathbf{\Sigma}}_{uu}^{-1} \hat{\mathbf{\Sigma}}_{uv}, \tag{15}$$

where

$$\begin{aligned} \hat{\mathbf{\Sigma}}_{vv} &= \frac{1}{T}\sum_{t=1}^{T} \hat{\boldsymbol{v}}_t \hat{\boldsymbol{v}}_t', \qquad & \hat{\mathbf{\Sigma}}_{uu} &= \frac{1}{T}\sum_{t=1}^{T} \hat{\boldsymbol{u}}_t \hat{\boldsymbol{u}}_t', \\ \hat{\mathbf{\Sigma}}_{uv} &= \frac{1}{T}\sum_{t=1}^{T} \hat{\boldsymbol{u}}_t \hat{\boldsymbol{v}}_t', \qquad & \hat{\mathbf{\Sigma}}_{vu} &= \frac{1}{T}\sum_{t=1}^{T} \hat{\boldsymbol{v}}_t \hat{\boldsymbol{u}}_t' \end{aligned}$$

and the $\hat{\boldsymbol{u}}_t$ and $\hat{\boldsymbol{v}}_t$ are the residual vectors from the auxiliary regressions. This yields two likelihood–ratio test statistics:

$$\begin{aligned} \text{trace} &= -T \sum_{i=r+1}^{n} \ln(1 - \hat{\lambda}_i) \\ \text{maximum eigenvalue} &= -T \ln(1 - \hat{\lambda}_{r+1}). \end{aligned}$$

The former is referred to as the trace test and contrasts the null of exactly r cointegrating relations with an alternative of n (i.e., that $\boldsymbol{\xi}_0$ is of full rank, if n is the number of elements in $\mathbf{TE}_t$). The latter is called the maximum eigenvalue test since it compares the r cointegrating relations null with an $r + 1$ alternative. We report the outcomes of both tests.

3.5 Convergence Regressions

The presence of cointegration indicates a long–run relationship between the efficiency series. However, this does not necessarily imply *convergence* of efficiency levels. To investigate the convergence aspect, we run simple cross–sectional regressions of time–averaged efficiency growth rates on the initial level of efficiency:

$$\mathrm{GRTE6590}_i = \alpha + \beta\, \mathrm{TE}_{i,1965} + \epsilon_i \tag{16}$$

where $\mathrm{GRTE6590}_i$ denotes the average growth rate of the efficiency level in country i between 1965 and 1990; and $\mathrm{TE}_{i,1965}$ is the level of efficiency of country i in 1965. In the tradition of Baumol and Barro, a negative and statistically significant coefficient on the initial level of efficiency can be interpreted as indicating convergence of efficiency levels.

However, Quah (1993, 1996), among others, criticizes such regressions on the grounds that they are plagued by Galton's "regression-to-the-mean" fallacy. We address this critcism by calculating coefficients of variation in the efficiency series along with the regression coefficients.

4 Application to OECD Countries

In this section, we apply the methodology outlined above to 26 OECD countries observed from 1965–90.

4.1 Data

We use the Penn World Table (Mark 5.6) data set, a revised and updated version of the data set compiled by Summers and Heston (1991). Our sample is comprised of 26 OECD countries observed over the period 1965–1990. The sample period is constrained to 26 years because of the lack of capital stock data. Although the OECD currently has 29 member countries, we do not use the data from the Eastern European nations, Czech Republic, Hungary, and Poland, since their data prior to their transition to capitalist societies are either unreliable or missing.

The aggregate output variable in our analysis is real GDP per capita in constant dollars expressed in 1985 international prices (called GDP). The labor–force participation rate and the per capita capital stock serve as measures of aggregate inputs (called LABOR and CAPITAL, respectively). The former can be retrieved from the Penn World Tables by dividing real GDP per capita by real GDP per worker. The latter is constructed as the product of capital stock per worker and the newly constructed LABOR variable.

4.2 Computation of Efficiency Levels

In the first step of our analysis, we construct the efficiency series for each country by DEA and SFA as described in sections 3.1 and 3.2. In both cases, we assume constant returns to scale (CRS). As noted earlier, an advantage of SFA is that it allows us to test assumptions like CRS. In our sample, the parametric restrictions associated with CRS cannot be rejected at usual significance levels. On the other hand, the data do reject the Cobb-Douglas restrictions, so our SFA results are based on a translog production frontier with CRS imposed.

Table 1 summarizes the DEA and SFA results, presenting each country's maximum and minimum efficiency rank and level as obtained from each method. Note that the efficiency level of the most efficient country in a given period as derived from SFA is not normalized to unity. Since each regression is modified using higher–order moments of the OLS residuals, the estimated efficiencies can take on values greater than one. In any case, there appears to be substantial agreement between DEA and SFA regarding the country ranks, especially regarding those countries which tend to operate near the frontier (e.g., Spain, Great Britain, Iceland, Luxembourg, and USA) and those which lag the farthest behind (e.g., Finland, Greece, Japan, Korea, and Norway).

4.3 Efficiency Change in Output Growth

Apart from evidence of productivity convergence, we are also interested in the importance of efficiency change for output growth. Improvements in efficiency represent movements toward the frontier, which should translate directly into greater output per unit of input, thereby contributing to an increased rate of output growth. If the impact of efficiency change on output growth is relatively large, then the current focus on capital accumulation as the engine of growth may be misguided. At the same time, such a result would focus attention on factors influencing technological diffusion and catch–up.

In table 2, we summarize R^2 measures from regressions of annual rates of per capita output growth on a constant and annual rates of efficiency change. A large percentage of variation in output growth can be explained by variation in efficiency change. The effects are particularly strong for smaller countries like Ireland, Iceland, Luxembourg, and New Zealand. But efficiency change seems to matter even for larger countries like Great Britain and Italy. While these results do not negate the importance of capital accumulation, they do suggest, however, that overlooking changes in efficiency may lead to seriously distorted conclusions about fundamental components of the growth process.

4.4 Unit–Root Tests

Next, we conduct the unit–root tests, estimating the DF test regression in equation (7) for each country series. Columns 2 and 3 of Table 3 contain the values of the DF $t-$statistics obtained from equation (7).[8] The unit–root null cannot be rejected for any country series, providing strong evidence of persistence in OECD efficiency levels.[9]

As a check on the DF results, we also conduct KPSS tests for level stationarity against a unit–root alternative. The values of the KPSS test statistic described in equation 8 are reported in columns 4 and 5 of Table 3. In general, the KPSS test results support the view of widespread persistence in efficiency levels of OECD countries. Using the DEA (SFA) series, the stationarity null is rejected in 15 (19) countries.

4.5 Cointegration Tests

Our cointegration empirics are focused on those country series for which the DF and KPSS tests reinforce each other. For the Engle-Granger tests we use all 15 DEA series and all 19 SFA series identified as exhibiting unit–root behavior, estimating two versions of equation (9), one with a trend term and a constant and one with just a constant. We estimate two regressions for each country–pair: once with an efficiency series as the regressor and once as the regressand.[10] Using the residuals from these regressions form the test regressions given in equation (10).[11]

The Engle–Granger tests indicate cointegration between efficiency series for small subset of countries. With the DEA-constructed efficiency series, we reject the null hypothesis of no cointegration at the 5 (10) percent level for only 5 (20) country–pairs. With SFA, there is slightly more evidence of cointegration; the null is rejected for 10 (31) country–pairs at the 5 (10) percent level. However, France and Greece is the only country–pair that exhibits cointegration in "both directions," which is a reflection of the Engle–Granger test's lack of invariance to the normalization in equation (9). Thus, it is difficult to draw any strong conclusions from the Engle–Granger tests about the long–run comovements in productive efficiency among OECD nations.

Dependence on the normalization is one disadvantage of the bivariate Engle–Granger approach. The inability to identify cointegrating relationships between more than two variables is another. While the FIML-based procedure of Johansen overcomes both of these defects, its application here

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[8] Since the USA defines the frontier every year in the DEA calculations, and because DEA calibrates the most efficient country to have an efficiency level of one, the DEA series for the USA does not exhibit enough variation for the application of a unit–root test.

[9] As noted in section 3.3 including drift and trend terms, or allowing for first-order dependence in the test regression disturbance, does not change the test outcomes.

[10] This amounts to a total of 420 regressions for the DEA series and a total of 684 regressions for the SFA series.

[11] There is very little evidence of serial dependence in the residuals of the Engle–Granger test regressions. Thus, we rely on the simple specification of these regressions and not include any further lagged differences in the residuals.

must be limited to subsets of the 26 countries since estimating a VAR for the entire OECD is infeasible. We apply Johansen's test to two groups of countries—the G–7 and the EU—which are distinguished, in part, by the degree to which their economies are interlinked.[12]

Table 6 summarizes the DEA FIML results, while table 7 presents those derived from SFA. Each table gives the values of trace and maximum–eigenvalue test statistics obtained from VARs comprised of the G–7 and EU efficiency series which were found to have a unit root.[13] For the purpose of comparison, we also summarize the Engle–Granger test outcomes for the same countries in tables 4 and 5.

Overall, the trace and maximum eigenvalue tests generate a much more coherent picture of the long–run relationships between country efficiencies. As far as the G–7 nations are concerned, there is little evidence of cointegration. Only one cointegrating relation is found (at the 10 percent level) using the DEA series, while just two are revealed among the SFA series. In sharp contrast, the FIML-based tests provide strong evidence of cointegration among EU members. With the DEA (SFA) series, we cannot reject the hypothesis of seven (ten) or less cointegrating relations at the 5 percent significance level. This picture appears reasonable in light of EU policies, such as assistance payments and technology transfers, directed toward the integration of poorer countries into the union.[14]

4.6 Convergence Regressions

Next, we investigate whether long–run relationships between efficiency levels are also characterized by convergence. Table 8 reports the results from convergence regressions on the G–7 and EU members listed in tables 6 and 7. The G–7 countries do not show any sign of convergence, using the DEA series, consistent with the absence of cointegration among these countries, while the SFA series indicate otherwise. Of course, results from regressions with samples sizes of 4 and 6 must be interpreted cautiously. On the other hand, the EU efficiency levels appear to converge regardless of how efficiency is measured. The estimated speeds of catch–up—over 4.5 percent based on DEA and

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[12] The G–7 members are Canada, France, Germany, Great Britain, Italy, Japan, and USA. The EU consists of Austria, Belgium, Denmark, Finland, France, Germany, Great Britain, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, and Sweden.

[13] For the DEA series, the G–7 group consists of Canada, Germany, Italy, and Japan. Austria, Belgium, Denmark, Finland, Germany, Italy, Luxembourg, and Spain are in the EU subset. For the SFA series, the G–7 and EU groups consist of Canada, France, Germany, Great Britain, Italy, and USA and of Belgium, Finland, France, Germany, Great Britain, Greece, Ireland, Italy, Luxembourg, Portugal, and Spain.

[14] Cf. Slaughter (1997) for a similar argument.

approximately 2.5 percent based on SFA—suggest that technological diffusion may be a relatively slow process.

As noted above, Quah has criticized estimated convergence regressions as examples of Galton's fallacy. Our response to this problem is to examine the temporal pattern of the coefficients of variation of the efficiency levels. These statistics for the G–7 and EU are displayed in figures 1 and 2. Declining coefficients of variation would tend to rebut Quah's critique and support a convergence result, and this is what we find in the EU. A similar pattern is exhibited by the coefficients of variation of the G–7 SFA series. Thus, where there is evidence of convergence from the regression analysis, it is reinforced by the corresponding coefficients of variation.

5 Conclusions

This paper intends to close an obvious gap in the empirical growth literature: the fact that differences in cross–country growth rates arise from differences in technology. The empirics in virtually everyone of the recent papers narrowly focus on the role of capital accumulation in generating economic growth.

We suggest a methodology to assess whether the economies under consideration display any reduction in their technological differences. Our approach is based on a frontier production function, which allows us to identify cross–country differences in productive efficiency. By examining the time–series properties of these country efficiency levels, we are able to determine (a) whether a long–run relationship exists among them, and (b) whether they exhibit convergence. Evidence of convergence would signal catch–up by less productive countries through the diffusion of technology.

We apply this methodology to a sample of 26 OECD countries observed over the period 1965–90. Overall, we find changes in country efficiency explain a large percentage of the variation in output growth, indicating the importance of a country's ability to absorb new technology. Regarding the time-series properties of the country efficiencies, unit–root tests provide evidence of a great deal of persistence across the OECD. In addition, cointegration tests suggest long–run relationships between the efficiency levels of the EU subset, which is consistent with the relatively greater integration of the EU economies. Finally, cross-sectional convergence regressions indicate catch–up by the less productive members of the EU.

Future research should proceed in at least two directions. Although it appears that efficiency levels exhibit a long–run relationship, no efforts have been made to explain the reasons for this.

It should be a worthwhile project to explore the underlying causes of this relationship. The other direction should focus on disaggregated data on the sectoral level. This might prove valuable in discovering which sectors emerge as the driving forces behind the convergence of productivity.

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Figure 1: Coefficients of Variation of Efficiency Levels of G–7 Countries

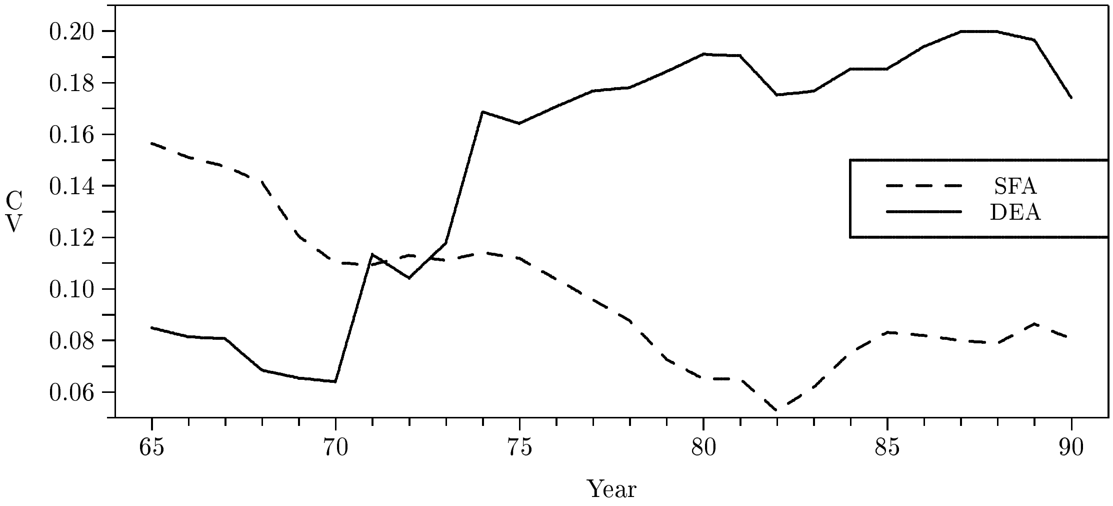

Figure 2: Coefficients of Variation of Efficiency Levels of EU Countries

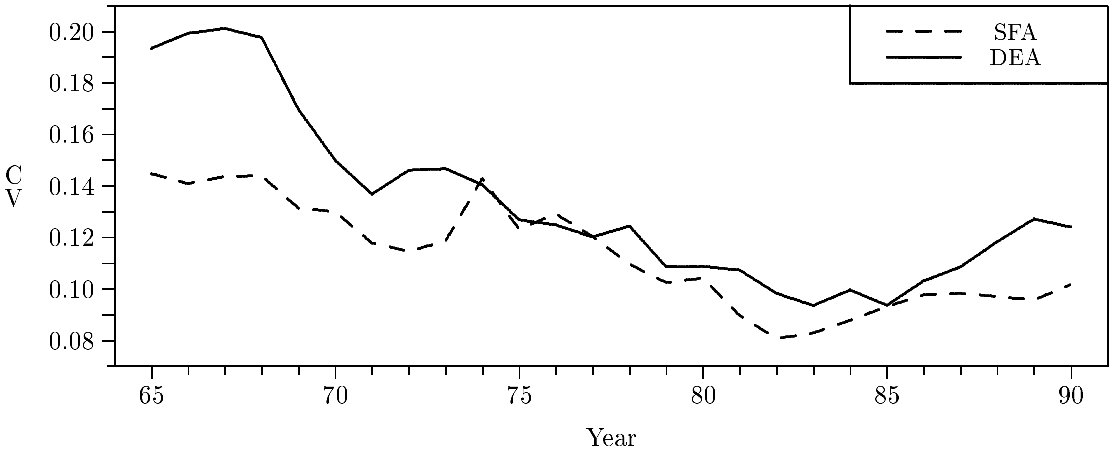

Table 1: Summary of Efficiency Measurement and Estimation

	DEA Series				SFA Series			
	Rank		Levels		Rank		Levels	
Country	Low	High	Max	Min	Low	High	Max	Min
Australia	16	7	87.6	75.1	15	7	93.7	83.2
Austria	23	6	88.5	69.7	21	13	86.3	80.4
Belgium	21	7	88.3	69.7	19	9	93.4	79.9
Canada	17	4	95.6	79.3	9	4	98.6	90.3
Switzerland	11	3	94.1	82.1	17	7	92.2	82.5
Germany	23	10	86.0	65.4	21	15	86.5	72.6
Denmark	23	14	76.1	65.4	23	16	84.9	72.0
Spain	18	1	100.0	75.7	18	2	99.2	85.6
Finland	26	20	74.9	49.3	25	22	82.5	61.2
France	16	8	87.9	79.3	17	8	92.1	83.2
Great Britain	13	1	100.0	83.1	7	2	103.5	90.6
Greece	26	24	63.3	54.9	26	24	73.1	57.3
Ireland	23	10	88.7	69.0	23	11	91.2	72.2
Iceland	7	1	100.0	86.2	14	1	111.7	87.0
Italy	22	7	89.2	67.5	22	6	95.2	72.3
Japan	26	18	73.9	56.3	26	23	74.6	58.9
Korea	26	16	73.3	47.9	26	15	84.8	63.0
Luxembourg	22	1	100.0	67.3	20	2	100.0	77.3
Mexico	19	5	95.5	73.9	17	3	98.5	83.2
Netherlands	11	4	92.9	82.6	9	2	97.0	90.6
Norway	24	9	86.2	61.0	24	14	88.3	65.7
New Zealand	22	8	91.3	71.2	21	4	95.9	81.3
Portugal	17	1	100.0	77.5	15	3	97.7	84.4
Sweden	20	11	83.4	73.0	19	9	89.9	81.9
Turkey	24	8	89.1	59.2	20	3	95.8	81.3
USA	1	1	100.0	100.0	2	1	113.2	101.2

Note: All efficiency levels are in per cent. The SFA efficiency levels are not normalized relative to the most efficient country.

Table 2: Efficiency Change in Output Growth

Country	Annual Output Growth Rate	R^2 DEA	SFA
Australia	1.97	0.21	0.30
Austria	2.90	0.05	0.03
Belgium	2.69	0.27	0.12
Canada	2.74	0.13	0.29
Switzerland	1.57	0.38	0.08
Germany	2.38	0.11	0.22
Denmark	2.00	0.18	0.32
Spain	2.95	0.32	0.25
Finland	3.08	0.57	0.32
France	2.58	0.06	0.10
Great Britain	2.17	0.38	0.37
Greece	3.17	0.34	0.30
Ireland	3.36	0.45	0.41
Iceland	3.06	0.44	0.71
Italy	3.14	0.46	0.32
Japan	4.64	0.20	0.08
Korea	7.37	0.35	0.32
Luxembourg	2.57	0.60	0.61
Mexico	2.21	0.23	0.41
Netherland	2.27	0.10	0.15
Norway	3.05	0.26	0.13
New Zealand	0.97	0.60	0.67
Portugal	4.53	0.08	0.24
Sweden	1.80	0.26	0.17
Turkey	2.90	0.21	0.10
USA	1.75	n.a.	0.23

Note: The figures in column 1 are in per cent. The R^2 measures in columns 2 and 3 are obtained by regressing the annual rate of per capita output growth on a constant and the annual rate of efficiency change obtained from the DEA or the SFA approach.

Table 3: Results from Unit–Root Tests

	Dickey-Fuller Test		Kwiatkowski et al. Test	
Country	DEA Series	SFA Series	DEA Series	SFA Series
Australia	0.5570	0.2803	0.9040^{**}	0.6739^{**}
Austria	−1.4262	−0.3926	1.3023^{**}	0.2918
Belgium	1.1140	2.6749	0.9771^{**}	1.3032^{**}
Canada	1.5726	0.5856	1.1991^{**}	1.0617^{**}
Switzerland	0.0777	0.3830	0.2864	0.1623
Germany	0.7348	0.3806	0.9810^{**}	0.8576^{**}
Denmark	−0.6559	0.2796	0.6700^{**}	0.3086
Spain	−1.1927	−1.0508	1.1727^{**}	1.1324^{**}
Finland	1.5212	1.6282	1.2628^{**}	1.2434^{**}
France	0.1507	1.0908	0.1383	1.0219^{**}
Great Britain	−0.0820	0.3601	0.3741^{*}	0.8010^{**}
Greece	0.3357	0.5054	0.1671	1.0608^{**}
Ireland	0.8980	1.3308	0.1075	1.1043^{**}
Iceland	−0.4891	−0.1458	0.1470	0.6532^{**}
Italy	1.4115	3.1386	1.0578^{**}	1.3072^{**}
Japan	−0.4588	0.1748	0.9412^{**}	0.3041
Korea	−0.1846	−0.8602	0.5194^{**}	0.3428
Luxembourg	1.5133	1.5347	1.1037^{**}	1.1324^{**}
Mexico	0.1032	0.2180	0.3676^{*}	0.4827^{**}
Netherlands	0.3605	0.7607	0.2434	0.2428
Norway	1.3874	0.9455	1.2507^{**}	1.1501^{**}
New Zealand	−0.8784	−1.4878	0.5319^{**}	0.7252^{**}
Portugal	0.6097	0.7241	0.1725	0.9277^{**}
Sweden	−0.4243	−0.7432	0.2291	0.2517
Turkey	0.1046	−0.4272	0.5945^{**}	0.7981^{**}
USA		−0.6041		0.6731^{**}

Note: ** denotes significance at 5% level, * at 10% level. The table entries in columns 2 and 3 are the DF test statistics on the slope coefficients of equation (7). Critical values can be found in Hamilton (1994), pp. 763-4. The entries in columns 4 and 5 are KPSS test statistics computed in equation (8). Critical values can be found in Kwiatkowski et al. (1992), p. 166.

Table 4: Results from Engle-Granger Cointegration Tests; DEA

Data Envelopment Analysis

G-7

Dependent	Independent Variable			
Variable	Canada	Germany	Italy	Japan
Canada				
Germany				*
Italy	*			*
Japan			*	

Data Envelopment Analysis

EU

Dependent	Independent Variable							
Variable	AUT	BEL	DNK	FIN	DEU	ITA	LUX	ESP
Austria								
Belgium			*					
Denmark		**			**			
Finland								
Germany								
Italy	**			**			**	**
Luxembourg								
Spain								

Note: ** denotes significance at 5% level; * at 10% level. The * in the upper panel in row Italy and column Canada means that the residuals from the regression of Italy's efficiency levels on Canada's efficiency levels do not exhibit a unit root, i.e., they are I(0). However, the same is not true for the reverse case of the regression of Canada's efficiency levels on Italy's efficiency levels.

Table 5: Results from Engle-Granger Cointegration Tests; SFA

Stochastic Frontier Analysis

G-7

Dependent Variable	Independent Variable Canada	 France	 Germany	 Great Britain	 Italy	 USA
Canada				*	*	
France			**			
Germany						
Great Britain						
Italy			*			
USA						

Stochastic Frontier Analysis

EU

Dependent Variable	Independent Variable BEL	 FIN	 FRA	 DEU	 GBR	 GRC	 IRL	 ITA	 LUX	 PRT	 ESP
Belgium											
Finland								*			
France		**		**		**	*	*		*	
Germany											
G. Britain											
Greece		**	**					**			
Ireland								*			
Italy		**		*		**	**				
Luxembourg											
Portugal											
Spain											

Note: ** denotes significance at 5% level; * at 10% level. The * in the upper panel in row Canada and column Italy means that the residuals from the regression of Canada's efficiency levels on Italy's efficiency levels do not exhibit a unit root, i.e., they are I(0). However, the same is not true for the reverse case of the regression of Italy's efficiency levels on Canada's efficiency levels.

Table 6: Results from Johansen Cointegration Tests; DEA

Data Envelopment Analysis

G-7: Canada, Germany, Italy, Japan

Eigen-values	Trace Test H_0 vs. H_1	Statistic	Max. EV Test H_0 vs. H_1	Statistic
0.6134	$r = 0$ vs. $r = 4$	44.13^{*}	$r = 0$ vs. $r = 1$	22.81
0.3601	$r \leq 1$ vs. $r = 4$	21.32	$r = 1$ vs. $r = 2$	10.71
0.2630	$r \leq 2$ vs. $r = 4$	10.61	$r = 2$ vs. $r = 3$	7.32
0.1280	$r \leq 3$ vs. $r = 4$	3.29		

EU: Austria, Belgium, Denmark, Finland,
Germany, Italy, Luxembourg, Spain

Eigen-values	Trace Test H_0 vs. H_1	Statistic	Max. EV Test H_0 vs. H_1	Statistic
1.0000	$r = 0$ vs. $r = 8$	1031.78^{**}	$r = 0$ vs. $r = 1$	748.41^{**}
0.9492	$r \leq 1$ vs. $r = 8$	283.36^{**}	$r = 1$ vs. $r = 2$	71.53^{**}
0.9475	$r \leq 2$ vs. $r = 8$	211.84^{**}	$r = 2$ vs. $r = 3$	70.74^{**}
0.9115	$r \leq 3$ vs. $r = 8$	141.09^{**}	$r = 3$ vs. $r = 4$	58.19^{**}
0.7904	$r \leq 4$ vs. $r = 8$	82.90^{**}	$r = 4$ vs. $r = 5$	37.50^{**}
0.6736	$r \leq 5$ vs. $r = 8$	45.40^{**}	$r = 5$ vs. $r = 6$	26.87^{**}
0.5236	$r \leq 6$ vs. $r = 8$	18.53^{**}	$r = 6$ vs. $r = 7$	17.80^{**}
0.0300	$r \leq 7$ vs. $r = 8$	0.73		

Note: r denotes the number of cointegrating relationships. Critical values are from Osterwald-Lenum (1992), p. 468, table 1. ** denotes significance at 5% level, * at 10% level.

Table 7: Results from Johansen Cointegration Tests; SFA

Stochastic Frontier Analysis

G-7: Canada, France, Germany, Great Britain, Italy, USA

Eigenvalues	Trace Test		Max. EV Test	
	H_0 vs. H_1	Statistic	H_0 vs. H_1	Statistic
0.9648	$r = 0$ vs. $r = 6$	168.91^{**}	$r = 0$ vs. $r = 1$	80.30^{**}
0.8036	$r \leq 1$ vs. $r = 6$	88.61^{**}	$r = 1$ vs. $r = 2$	39.06^{**}
0.5925	$r \leq 2$ vs. $r = 6$	49.54^{*}	$r = 2$ vs. $r = 3$	21.54
0.4467	$r \leq 3$ vs. $r = 6$	28.00^{*}	$r = 3$ vs. $r = 4$	14.20
0.3054	$r \leq 4$ vs. $r = 6$	13.79	$r = 4$ vs. $r = 5$	8.75
0.1897	$r \leq 5$ vs. $r = 6$	5.05		

EU: Belgium, Finland, France, Germany, Great Britain,
Greece, Ireland, Italy, Luxembourg, Portugal, Spain

Eigenvalues	Trace Test		Max. EV Test	
	H_0 vs. H_1	Statistic	H_0 vs. H_1	Statistic
1.0000	$r = 0$ vs. $r = 11$	7226.08^{**}	$r = 0$ vs. $r = 1$	689.32^{**}
1.0000	$r \leq 1$ vs. $r = 11$	6536.76^{**}	$r = 1$ vs. $r = 2$	702.85^{**}
1.0000	$r \leq 2$ vs. $r = 11$	5833.90^{**}	$r = 2$ vs. $r = 3$	769.78^{**}
1.0000	$r \leq 3$ vs. $r = 11$	5064.13^{**}	$r = 3$ vs. $r = 4$	769.78^{**}
1.0000	$r \leq 4$ vs. $r = 11$	4294.35^{**}	$r = 4$ vs. $r = 5$	720.94^{**}
1.0000	$r \leq 5$ vs. $r = 11$	3573.40^{**}	$r = 5$ vs. $r = 6$	720.94^{**}
1.0000	$r \leq 6$ vs. $r = 11$	2852.46^{**}	$r = 6$ vs. $r = 7$	756.39^{**}
1.0000	$r \leq 7$ vs. $r = 11$	2096.07^{**}	$r = 7$ vs. $r = 8$	733.61^{**}
1.0000	$r \leq 8$ vs. $r = 11$	1362.46^{**}	$r = 8$ vs. $r = 9$	673.15^{**}
1.0000	$r \leq 9$ vs. $r = 11$	689.31^{**}	$r = 9$ vs. $r = 10$	657.28^{**}
0.7367	$r \leq 10$ vs. $r = 11$	32.03^{**}		

Note: r denotes the number of cointegrating relationships. Critical values are from Osterwald-Lenum (1992), p. 468, table 1. ** denotes significance at 5% level, * at 10% level.

Table 8: Estimation of Convergence Regressions

Dependent variable: growth rate of DEA efficiency series

	Country Groups	
Sample:	G-7	EU
Observations:	4	8
CONSTANT	-0.0123	0.0399^{**}
	(0.0452)	(0.0096)
$\mathrm{TE}_{i,1965}$	0.0239	-0.0482^{**}
	(0.0639)	(0.0126)
R^2	0.065	0.708
SEE	0.007	0.005

Dependent variable: growth rate of SFA efficiency series

	Country Groups	
Sample:	G-7	EU
Observations:	6	11
CONSTANT	0.0252^{**}	0.0238^{**}
	(0.0071)	(0.0062)
$\mathrm{TE}_{i,1965}$	-0.0250^{**}	-0.0239^{**}
	(0.0079)	(0.0077)
R^2	0.714	0.516
SEE	0.002	0.003

Note: Standard errors are in parentheses. ** denotes significance at 5% level. Composition of the country groups: DEA: the G-7 group consists of Canada, Germany, Italy, and Japan; the EU group consists of Austria, Belgium, Denmark, Finland, Germany, Italy, Luxembourg, and Spain; SFA: the G-7 group consists of Canada, France Germany, Great Britain, Italy, and the USA; the EU group consists of Belgium, Finland, France, Germany, Great Britain, Greece, Ireland, Italy, Luxembourg, Portugal, and Spain.

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