MAPPING THE TWO FACES OF R&D: PRODUCTIVITY GROWTH IN A PANEL OF OECD INDUSTRIES

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Abstract

Many writers have claimed that research and development (R&D) has two 'faces'. In addition to the conventional role of stimulating innovation, R&D enhances technology transfer by improving the ability of firms to learn about advances in the leading edge ('absorptive capacity'). In this paper we explore this idea empirically using a panel of industries across twelve OECD countries. We find evidence that R&D is statistically and economically important in this catch up process as well as stimulating innovation directly. Human capital also plays an major role in productivity growth, but we only find a small impact of trade. Because R&D matters so much for growth through catch-up, social rates of return have been underestimated by studies that focus only on the U.S.

JEL CLASSIFICATION: O0, O3, O4

KEYWORDS: R&D; human capital; Total Factor Productivity; convergence

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1 Introduction

This paper provides empirical evidence that there are two roles or 'faces' of research and development (R&D) activity. The first of these roles is in stimulating innovation, and has received most attention in the existing empirical literature. The second role is in facilitating the imitation of others' discoveries. Some knowledge is 'tacit', difficult to codify in manuals and textbooks, and hard to acquire without direct investigation. By actively engaging in R&D in particular intellectual or technological field, one acquires such tacit knowledge and can more easily understand and assimilate the discoveries of others. An example, cited by Arrow (1969), is the jet engine: when plans were supplied by the British to the Americans during the Second World War, it took ten months for them to be redrawn to conform to American usage. The importance of 'tacit knowledge' or 'absorptive capacity' has been a central theme in the literatures on the history and microeconomics of technology.[1] A large number of theoretical models have been proposed in which R&D has both an innovative and imitative role.[2] However, there has been almost no rigorous econometric work assessing the statistical significance and quantitative importance of the 'second face of R&D'. This is especially true in the international dimension of technology transfer.[3] This paper provides such an analysis using a "three-dimensional" panel of industries in twelve OECD countries since 1970. We find strong evidence that R&D has a "second face": country-industries lagging behind the productivity frontier catch-up particularly fast if they invest heavily in R&D.

We present an empirical framework in which innovation and technology transfer provide two potential sources of productivity growth for countries behind the technological frontier. A country's distance from the technological frontier is used as a direct measure of the po-

[1] For further discussion, see, for example, David (1992) and Rosenberg (1982).

[2] See, for example, Aghion and Howitt (1997), Cohen and Levinthal (1989), Grossman and Helpman (1991), Howitt (2000), Neary and Leahy (1999), and Segerstrom (1991).

[3] There is some firm-level evidence of absorptive capacity. Jaffe (1986) has results suggesting that high R&D U.S. firms benefit most in terms of productivity from his spillover pool. Geroski, Machin and Van Reenen (1993) found that UK firms with a past history of innovation were those most likely to benefit from the innovations of other firms. However, there has been no systematic analysis of implications for industry productivity growth and social rates of return to R&D across countries.

tential for technology transfer, where the frontier is defined for each industry as the country with the highest level of total factor productivity (TFP). We examine whether R&D has a direct effect upon a country's rate of TFP growth (innovation), and whether R&D's effect on TFP growth depends upon a country's distance from the frontier (technology transfer). The further a country lies behind the technological frontier, the greater the potential for R&D to increase TFP growth through technology transfer from more advanced countries.[4] We argue that the social rate of return to R&D has generally been underestimated, in so far as most studies have focused on the USA, which is typically (but not exclusively) the technological leader in our data.

The paper relates to two other existing literatures - on the impact of R&D spillovers and the convergence debate. First, we build on the existing empirical literature examining the role of R&D in explaining rates of productivity growth, particularly through knowledge spillovers.[5] Some papers have left the precise spillover mechanism unspecified, others have sought a "paper trail" through use of patent technology class, patent citations, and international trade as routes for technology transfer.[6] This paper extends the conventional specification to allow for a 'second face' of R&D activity. We employ a direct measure of distance from the technological frontier based on relative TFP levels to allow for spillovers of knowledge from both formal R&D investments and informal sources of productivity growth (e.g. learning by doing).[7]

The paper also relates to the literature on the convergence of Total Factor Productivity (TFP). Within the neoclassical Solow-Swan model, income convergence is explained by

[4]See Cameron (1996) for an analysis along these lines of Japan and the United States and Cameron, Proudman, and Redding (1998) for an analysis of the United Kingdom and United States.

[5]Classic references include Griliches (1980) and Griliches and Lichtenberg (1984). See Hall and Mairesse (1995) for a recent analysis using French data and Mohnen (1996) for a survey of this literature.

[6]See, inter alia, unspecified: Bernstein and Mohnen (1998); patent class: Bransetter (1996); patent applications: Eaton and Kortum (1996, 1999); patent citations: Jaffe and Trajtenberg (1998); FDI: Lichtenberg and Von Pottelsberghe de Potterie (1996), trade: Bayoumi *et al.* (1996), Keller (1997, 1999), Coe and Helpman (1995), Coe, Helpman, and Hoffmaister (1997).

[7]A wide range of empirical evidence suggests that the informal activities not captured in R&D statistics play an important role in determining productivity levels (see, for example, Lucas (1993) for an examination of learning by doing).

capital accumulation.[8] An older literature dating back to Gerschenkron (1952) and Nelson and Phelps (1966) emphasises the importance of technology transfer and the role of 'absorptive capacity',[9] and recent years have seen a resurgence of interest in cross-country differences in aggregate productivity.[10] A number of writers have examined the effects of human capital and international trade on aggregate rates of growth.[11] This paper examines the disaggregated forces underlying country-level performance, and analyses the determinants of productivity growth at the industry-level. The use of superlative index number measures of TFP (rather than those based on a Cobb-Douglas technology) strengthens findings of productivity convergence at the industry-level.[12]

The structure of the paper is as follows. Section 2 introduces the theoretical framework. Section 3 discusses the econometric specification. Section 4 introduces the data and undertakes some data description. Section 5 presents the econometric results relating to the two faces of R&D and quantifies their importance. Section 6 examines the robustness of the results, and section 7 offers some concluding comments.

Our results are easy to summarise. We find evidence of R&D effects on both rates of innovation and technology transfer across a wide range of specifications. These results are robust to a number of different adjustments in the measurement of TFP (e.g. controlling for cross-country differences in hours, skills levels and markups of price over marginal cost). Human capital has an important effect on rates of both innovation and technology transfer whereas international trade has little robust influence on productivity.

[8] See, for example, Mankiw, Romer, and Weil (1992).

[9] See also Abramovitz (1986) and Benhabib and Spiegel (1994).

[10] See, in particular, Acemoglu and Zillibotti (1998), Hall and Jones (1998), Parente and Prescott (1994), (2000), and Prescott (1998).

[11] Those concerned with human capital and growth include Barro and Lee (1994), Benhabib and Spiegel (1994), Krueger and Lindahl (1998), and Mankiw, Romer, and Weil (1992). Edwards (1998), Frankel and Romer (1999), and Harrison (1996) analyse the relationship between international trade and economic growth.

[12] The productivity convergence literature includes Bernard and Jones (1996a, 1996b), Dollar and Wolff (1994), and Harrigan (1997, 1999). See also van Ark and Pilat (1993), Dowrick (1989), Jorgenson and Kuroda (1990), Hansson and Henrekson (1994), O'Mahony (1998), and Pilat (1996).

2 Theoretical Framework

This section outlines the theoretical framework underlying our modelling strategy (for a complete derivation, see Griffith, Redding and Van Reenen (2000)). Denote countries by $i = 1, ..., N$ and manufacturing industries by $j = 1, ..., J$. Value added (Y) in each sector at time t is produced with labour (L) and physical capital (K) according to a standard neoclassical production technology,

$$Y_{ijt} = A_{ijt} F_j(L_{ijt,} K_{ijt}) \tag{1}$$

where A is an index of technical efficiency or Total Factor Productivity (TFP). $F_j(.,.)$ is assumed to be homogenous of degree one and to exhibit diminishing marginal returns to the accumulation of each factor alone and we allow it to vary across sectors. We allow TFP (A) to vary across countries, sectors and time; we term the economy with the highest level of TFP in sector j at time t the frontier ($i = F$) and denote this A_{Fjt}.

The starting point for our analysis is the empirical literature on R&D and productivity growth at the firm and industry-level.[13] TFP in equation (1) is assumed to be a function of the R&D knowledge stock (G). Taking logarithms and differencing with respect to time, the rate of TFP growth depends on the rate of growth of the R&D knowledge stock,[14]

$$\triangle \ln A_{ijt} = \eta \triangle \ln G_{ijt} + \gamma X_{ijt-1} + u_{ijt} \tag{2}$$

where $\eta \equiv (dY/dG)(G/Y)$ is the elasticity of output with respect to the R&D knowledge stock and u is a stochastic error. X is a vector of control variables, which includes human capital and international trade in the empirical application to follow. For small rates of depreciation of R&D knowledge, equation (2) may be expressed as follows,[15]

[13] See, in particular, Griliches (1980) and Griliches and Lichtenberg (1984).

[14] The substantive assumption here is separability between R&D and other factors of production. The alternative approach embracing non-separability is followed by authors such as Bernstein and Nadiri (1989) and Nadiri and Kim (1996).

[15] In continuous time, $\dot{G}_{ijt} = R_{ijt} - \varphi G_{ijt}$, where φ is the rate of depreciation of R&D knowledge. If one explicitly assumes an R&D depreciation rate, equation (2) can be estimated directly. We adopted this approach as a robustness test, but note the great uncertainty surrounding the appropriate rate of depreciation for knowledge.

$$\triangle \ln A_{ijt} = \rho \left(\frac{R}{Y}\right)_{ijt-1} + \gamma X_{ijt-1} + u_{ijt} \tag{3}$$

where $\rho \equiv (dY/dG)$ is the rate of return to R&D. The theoretical rationale for this equation is provided by models of endogenous innovation and growth.[16] We augment the conventional specification in equation (3) in two ways. First, following the convergence literature, we introduce technology transfer as a source of productivity growth for countries behind the technological frontier. Second, there is a theoretical literature which suggests that R&D activity plays an important role in technology transfer.[17] Griffith, Redding, and Van Reenen (2000) present a general equilibrium model of endogenous growth through increasing productivity following Aghion and Howitt (1992, 1997) that incorporates both of these considerations. The conventional quality ladder model is augmented to allow the size of innovations to be a function of the distance behind the technological frontier. The rate of return to R&D activity depends on distance from the technological frontier, and an equation for TFP growth of the following form is derived,

$$\begin{aligned} \triangle \ln A_{ijt} = \rho_1 \left(\tfrac{R}{Y}\right)_{ijt-1} + \text{technology transfer} & \underbrace{\beta \triangle \ln A_{Fjt} - \delta_1 \ln \left(\frac{A_i}{A_F}\right)_{jt-1}} \\ - \text{absorptive capacity} & \underbrace{\delta_2 \left(\frac{R}{Y}\right)_{ijt-1} \ln \left(\frac{A_i}{A_F}\right)_{jt-1}} \\ & + \gamma X_{ijt-1} + u_{ijt} \end{aligned} \tag{4}$$

The second and third terms on the right-hand side of this expression capture technology transfer. For non-frontier countries, relative TFP $\left(ln\left(A_i/A_F\right)_{jt-1}\right)$ is negative; the more negative is relative TFP, the further a country lies behind the frontier, and the greater the potential for technology transfer. Therefore, with technology transfer, the estimated coefficient on relative TFP (δ_1) should be negative. The presence of the term $\beta \triangle \ln A_{Fjt}$ allows the contemporaneous rate of TFP growth in the frontier to have a direct effect on

[16] See, for example, Romer (1990) and Aghion and Howitt (1992).
[17] See, in particular, Cohen and Levinthal (1989).

TFP growth in non-frontier countries. As will be discussed further below, the specification in equation (4) is consistent with an ADL(1,1) and long-run cointegrating relationship between TFP in frontier and non-frontier countries. The fourth term on the right-hand side is an interaction term, and captures the second face of R&D. If R&D aids technology transfer, its rate of return will be higher in non-frontier countries. In these countries, R&D not only generates TFP growth through innovation, but also facilitates technology transfer. The smaller is $ln\left(A_i/A_F\right)_{jt-1}$, the further a country lies behind the frontier, and the greater the potential for technology transfer. Therefore, if there is a second face of R&D, the estimated coefficient on the interaction term (δ_2) should be negative. The speed of technology transfer in equation (4) is given by $\delta \equiv \delta_1 + \delta_2.(R/Y)_{ijt-1}$, while the rate of return to R&D (from both innovation and technology transfer) is $\rho \equiv \rho_1 - \delta_2.\ln(A_i/A_F)_{ijt-1}$.[18]

The expression for TFP growth in the frontier remains exactly the same as in the conventional specification (when $A_i = A_F$, equation (4) reduces to (3) where $\rho = \rho_1$). Combining equation (4) for frontier and non-frontier countries, one obtains a first-order difference equation for the evolution of relative TFP,

$$\begin{aligned} \triangle \ln\left(\tfrac{A_i}{A_F}\right)_{jt} = \rho_1\left(\left(\tfrac{R}{Y}\right)_{ijt-1} - \left(\tfrac{R}{Y}\right)_{Fjt-1}\right) + \beta\triangle \ln A_{Fjt} \\ - \left(\delta_1 + \delta_2\left(\tfrac{R}{Y}\right)_{ijt-1}\right)\ln\left(\tfrac{A_i}{A_F}\right)_{jt-1} \\ +\gamma\left(X_{ijt-1} - X_{Fjt-1}\right) + \left(u_{ijt} - u_{Fjt}\right) \end{aligned} \tag{5}$$

In steady-state equilibrium, TFP in a sector j in all countries i will grow at the same constant rate, equal to TFP growth in the frontier ($\triangle \ln A_{ij} = \triangle \ln A_{Fj}$ and $\triangle \ln(A_i/A_F)_j = 0$ for all i). The model allows for countries to endogenously switch between being non-frontier and frontier countries. In steady-state equilibrium, the frontier country will be whichever of the countries has the highest rate of TFP growth from innovation alone in sector j (as a result of R&D activity (R/Y) and the value of the control variables (X) in equation (4)). TFP growth from innovation and technology transfer in each non-frontier country

[18]See also Cameron (1996) and Cameron, Proudman, and Redding (1998).

will exactly equal TFP growth from innovation alone in the frontier. Setting the rate of growth of relative TFP in equation (5) equal to zero, we obtain the following expression for steady-state equilibrium relative TFP,[19]

$$\ln\left(\frac{A_i}{A_F}\right)^*_{jt} = \frac{\rho_1\left[\left(\frac{R}{Y}\right)_{ijt} - (1-\beta)\left(\frac{R}{Y}\right)_{Fjt}\right] + \gamma\left[X_{ijt} - (1-\beta)X_{Fjt}\right]}{\left(\delta_1 + \delta_2.\left(\frac{R}{Y}\right)_{ijt}\right)} \tag{6}$$

3 Econometric Specification

Equation (4) provides the starting point for the econometric estimation. This specification is an Equilibrium Correction Model (ECM) representation of a cointegrating relationship between TFP in frontier and non-frontier countries.[20] This representation has many attractive statistical properties. Consider an ADL(1,1) model where own TFP is cointegrated with frontier TFP,

$$\ln A_{ijt} = \alpha_1 \ln A_{ijt-1} + \alpha_2 \ln A_{Fjt} + \alpha_3 \ln A_{Fjt-1} + u_{ijt}. \tag{7}$$

Under the assumption of long-run homogeneity ($\frac{\alpha_2+\alpha_3}{1-\alpha_1} = 1$), this can be represented as follows,

$$\triangle \ln A_{ijt} = \alpha_2 \triangle \ln A_{Fjt} - (1-\alpha_1)\ln\left(\frac{A_i}{A_F}\right)_{jt-1} + u_{ijt}. \tag{8}$$

Ignoring R&D, this is equation (4), where $\alpha_2 = \beta$, and $1 - \alpha_1 = \delta_1$. In (4) equation (8) is augmented with a term for the R&D intensity, the coefficient on relative TFP $(1 - \alpha_1)$ is allowed to be a function of R&D intensity, and we include a vector of control variables. It is clear from this discussion that the coefficient on the relative TFP term measures the speed of convergence to long-run equilibrium, and an explicit value for the long-run or steady-state equilibrium value of relative TFP was derived in the previous section.

There will clearly be unobserved country-industry characteristics, which affect rates of TFP growth and are not captured by our model. Moreover, it is likely that these unobserved country-industry characteristics will be correlated with the explanatory variables in (4).

[19]Note that the numerator of (6) is negative and the denominator positive: $\ln(A_i/A_F)$ is less than zero for a non-frontier country.

[20]See Hendry (1996).

For example, features of the production technology in particular sectors of a country may result in a high rate of TFP growth in precisely the industries characterised by high R&D intensities. We control for unobserved heterogeneity that is correlated with the explanatory variables by allowing the error term (u_{ijt}) to include a country-industry specific fixed effect (ψ_{ij}). There may also be common macroeconomic shocks which affect rates of TFP growth in all countries, and we therefore allow the error term (u_{ijt}) to include a full set of time dummies (T_t),

$$u_{ijt} = \psi_{ij} + T_t + \varepsilon_{ijt}$$

where ε_{ijt} is a serially uncorrelated error. Substituting for u_{ijt} in equation (4), we obtain our final econometric specification of TFP growth in sector j of a non-frontier country,

$$\begin{aligned} \triangle \ln A_{ijt} = \beta \triangle \ln A_{Fjt} - \delta_1 \ln \left(\tfrac{A_i}{A_F}\right)_{jt-1} - \delta_2 \left[\left(\tfrac{R_i}{Y_i}\right) \ln \left(\tfrac{A_i}{A_F}\right)\right]_{jt-1} \\ + \rho_1 \left(\tfrac{R}{Y}\right)_{ijt-1} + \gamma X_{ijt-1} + \psi_{ij} + T_t + \varepsilon_{ijt}. \end{aligned} \tag{9}$$

As discussed above, there is no potential for technology transfer to the frontier. TFP growth in sector j in the frontier is thus modelled as in the conventional specification,

$$\Delta \ln A_{Fjt} = \psi_{Fj} + \rho \left(\frac{R}{Y}\right)_{Fjt-1} + \gamma X_{Fjt-1} + T_t + \varepsilon_{Fjt}. \tag{10}$$

The equation for the frontier economy is stacked together with the equations for the non-frontier economies with the cross-equation restrictions on the R&D intensity variable imposed. We are careful to examine the robustness of the results to dropping the frontier observations in case the cross-equation restrictions are invalid.[21] Our baseline results estimate equations (9) and (10) using the within group estimator (least-squares dummy variable).

There are several issues involved with this econometric strategy. First, note that we do not claim that R&D is strictly exogenous. Shocks to the economic environment (ε_{ijt}) can certainly feedback into the firm's R&D decision. Rather, we are assuming that current shocks do not influence past levels of R&D, i.e. that $cov\left(\varepsilon_{ijt}, \left(\tfrac{R}{Y}\right)_{ijt-1}\right) = 0$ and

[21] Griffith, Redding and Van Reenen (2000) discuss this in more detail.

$\text{cov}\left(\varepsilon_{ijt}, \ln\left(\frac{A_i}{A_F}\right)_{jt-1}\right) = 0$. These weak exogeneity assumptions would be violated if, for example, firms correctly predicted future shocks and violations would be reflected in serial correlation of the ε_{ijt} term. We therefore present tests for serial correlation in all the results below.

Second, measurement error could lead to bias in the estimated coefficients. In the robustness section, we investigate the importance of this bias with an instrumental variables estimator. A complementary approach uses data on some of the variables suggested as sources of measurement error in the TFP literature.

Third, the model implies that it is not the *identity* of the frontier country that is important (equation (9)), but the measure of *distance from the technological frontier* which captures the potential for technology transfer. Our analysis does not preclude technological transfer from countries with levels of productivity higher than one's own but lower than the frontier. All we require is that distance from the technological frontier is correlated with the potential for technology transfer. We establish the robustness of our results to the use of alternative measures of the latter variable, using for example the average of the countries with the two highest TFP levels in defining the location of the frontier, rather than simply the country with the highest relative TFP.

Fourth, the model considered here is related to the convergence literature. As is clear from the ADL(1,1) representation of the model above, the existence of a long-run cointegrating relationship between TFP in each non-frontier country and TFP in the frontier means that the analysis is most closely related to the time-series literature on convergence.[22] It is true that the long-run relationship between TFP levels implies conditional β-convergence in *relative* TFP (see equation (5)). That is, controlling for the determinants of steady-state relative TFP, those countries with the lowest initial levels of *relative* TFP will experience the highest rates of growth of *relative* TFP.[23] However, this is simply an implication of the

[22] See, in particular, Bernard and Durlauf (1995, 1996).

[23] For further discussion of β-convergence and the alternative concept of σ-convergence in the context of the cross-country growth literature, see Barro and Sala-i-Martin (1995).

time-series convergence in TFP levels. We do not estimate the equation for *relative* TFP growth, and our findings of a long-run relationship between TFP levels are not subject to Galton's Fallacy.[24] It is also worth noting that the model does not necessarily imply σ-convergence in relative TFP. That is, depending upon the initial and steady-state relative TFP distributions, the cross-country sample standard deviation of relative TFP may either rise, decline, or remain constant over time. In actual fact, the sample period is characterised by σ-convergence in the majority of industries. However, this is a feature of the data, and not a necessary implication of a long-run relationship between TFP in each non-frontier country and TFP in the frontier.

Finally, there may be finite sample biases using the within group estimator even if the regressors are all pre-determined. The results in Nickell (1981), however, show that the magnitude of this bias diminishes in the length of the time-series element of the panel. Since our sample runs for 19 years, the size of this bias is likely to be small.

4 Data Description

4.1 Data sources and sample size

The data used in the empirical application comes from a number of sources. The main data source is the OECD International Sectoral Data Base (ISDB) which provides information at the two-digit industry level on value added, labour and capital stocks. We have combined this basic data with data on R&D expenditure from the OECD ANBERD dataset. To measure R&D we use business expenditure on research and development (BERD). This includes all R&D performed by the business sector (from all sources of finance, including government

[24]Galton examined the heights of fathers and sons, and found that the sons of tall fathers tended to be shorter than their fathers, while the fathers of tall sons tended to be shorter than their sons. Both findings may be explained in terms of mean reversion, and do not imply that the cross-section disperson of male heights is falling over time. For further discussion of Galton's Fallacy in a growth context, see Friedman (1992) and Quah (1993). We estimate an equation for TFP growth in non-frontier countries, which is the Equilibrium Correction Model (ECM) representation of a long-run cointegrating relationship between non-frontier and frontier TFP. Findings of technology transfer (a statistically significant coefficient on the relative TFP term) establish dynamic adjustment towards this long-run relationship.

subsidies).[25] We also draw on information from several other datasources. For information on occupational skills we use the UNIDO database (see Berman, Bound and Machin, 1998), for education we use aggregate data from Barro and Lee (1994) and industry data from Machin and Van Reenen (1998). Trade data is derived from the OECD Bilateral Trade Database.

Our sample consists of twelve countries over the period 1974-1990. For some of the countries, information is available for nine two-digit industries (ISIC 31-39), while for others ISIC 38 is additionally broken down into five three-digit industries. Where the more disaggregated information is available for the three-digit industries we use it. At the same time, careful attention is paid to the robustness of the results to alternative samples of countries and industries. See Appendix A for details.

4.2 TFP growth and relative levels across countries and industries

We calculate the growth rate of TFP ($\triangle TFP_{ijt}$, the empirical counterpart to $\triangle \ln A_{ijt}$ in section 2) and the level of TFP in country i relative to the frontier ($RTFP_{ijt}$, the empirical counterpart to $\ln(A_i/A_F)_{jt}$ above). In each case, we use the superlative index number approach of Caves et. al. (1982a,b), which allows for a flexible specification of the production technology. Our baseline measures of TFP growth and relative levels of TFP use the raw data from the ISDB. However, in the literature much attention is paid to how TFP is measured and in particular how to correct for differences across countries in hours worked, skills levels, mark-ups, capacity utilization, and other factors. We use a number of different measures which adjust for these factors to confirm the robustness of our results. The way in which our baseline measure is calculated is described here; the way in which the adjusted measures are calculated is described in Appendix A.

TFP growth is measured by a superlative index derived from the translog production

[25] A concern is that the definition of "research and development" in the lower productivity countries could include the adoption costs of high tech capital goods. This is unlikely since only 10% or less of R&D is capital investment. Nevertheless we check for this in the empirical section by including lagged investment in soem specifications.

function,[26]

$$\triangle TFP_{ijt} = \ln\left(\frac{Y_{ijt}}{Y_{ijt-1}}\right) - \frac{1}{2}(\alpha_{ijt} + \alpha_{ijt-1}) \ln\left(\frac{L_{ijt}}{L_{ijt-1}}\right) - \left(1 - \frac{1}{2}(\alpha_{ijt} + \alpha_{ijt-1})\right) \ln\left(\frac{K_{ijt}}{K_{ijt-1}}\right) \tag{11}$$

where α_{ijt} is the share of labour in value-added, Y_{ijt} denotes real value-added (converted to US dollars using an economy-wide PPP), L_{ijt} is number of workers employed, and K_{ijt} is real capital stock (converted to US dollars using a capital PPP). One problem we face in measuring TFP is that the share of labour in value-added, α_{ijt}, is quite volatile. This is suggestive of measurement error, and we therefore follow Harrigan (1997) in exploiting the properties of the translog production function to smooth the observed labour shares. Under the assumption of a translog production function and standard market-clearing conditions, α_{ijt} can be expressed as a function of the capital-labour ratio and a country-industry constant,[27]

$$\alpha_{ijt} = \xi_{ij} + \phi_j \ln\left(K_{ijt}/L_{ijt}\right). \tag{12}$$

If actual labour shares deviate from their true values by an i.i.d. measurement error term, then the parameters of this equation can be estimated by fixed effects panel data estimation, where we allow the coefficient on the capital-labour ratio to vary across industries j. The fitted values from this equation are then used as the labour cost shares in our calculation of (11) and below. Mean rates of TFP growth by country and industry are reported in Table A2 in Appendix 1. We find substantial heterogeneity in rates of TFP growth across countries and industries, and this variation will be used to identify the parameters of interest in the econometric analysis that follows.

We measure the level of TFP in each country relative to the frontier using an analogous superlative index number derived from the translog production function. We begin by evaluating the level of TFP in each country relative to a common reference point - the geometric mean of all other countries. This is done for each industry-year (e.g. we measure TFP in

[26] See Caves et al. (1982b). One of the classic references on measuring TFP growth is Solow (1957).
[27] See Caves *et al.* (1982b) and Harrigan (1997).

the US chemicals industry in 1980 relative to the geometric mean of the chemical industry of all other countries in 1980). This measure of TFP is given by,

$$MTFP_{ijt} = \ln\left(\frac{Y_{ijt}}{\bar{Y}_{jt}}\right) - \tilde{\sigma}_{ijt}\ln\left(\frac{L_{ijt}}{\bar{L}_{jt}}\right) - (1-\tilde{\sigma}_{ijt})\ln\left(\frac{K_{ijt}}{\bar{K}_{jt}}\right) \tag{13}$$

where an upper bar above a variable denotes a geometric mean; that is, $\bar{Y}_{jt}$, $\bar{L}_{jt}$, $\bar{K}_{jt}$, are the geometric means of output, labour and capital in industry j at time t respectively. The variable $\tilde{\sigma}_{ijt} = 1/2(\alpha_{ijt}+\bar{\alpha}_{jt})$ is the average of the labour share in country i and the geometric mean labour share, where we again exploit the properties of the translog production function to smooth observed labour shares (see equation (12) above).

We define the frontier as the country with the highest value of TFP relative to the geometric mean in each industry (j) at time (t) (denoted $MTFP_{Fjt}$). Subtracting $MTFP_{Fjt}$ from $MTFP_{ijt}$, we obtain a superlative index number measure of relative TFP (denoted $RTFP_{ijt}$, the empirical counterpart to $\ln\left(A_i/A_F\right)_{jt}$ in section 2),[28]

$$RTFP_{ijt} = MTFP_{ijt} - MTFP_{Fjt}. \tag{14}$$

To illustrate our method, Figure 1 plots relative TFP (RTFP) for one industry - Paper, Printing and Publishing (ISIC 34). The USA was the frontier country throughout our sample period except in the final year when it is pushed into second place by the Netherlands. In this industry most counties have narrowed the gap with the USA. Japan is notable for starting off as one of the countries furthest from the USA in 1973 and closing about half of the TFP gap by 1990. Other countries have not been so successful. Canada and Denmark have not improved their position relative to the USA, and Britain did not start catching up until the 1980s. The picture varies by industry, but Table 1 shows which country has the highest (the frontier) and second highest level of relative TFP in 1971, 1981, and 1990.

In some industries, the identity of the frontier and the country with the next highest level of relative TFP remains constant over time (e.g. ISIC 383, and 384), while in other industries

[28]Note that equation (13) may be used to obtain a bilateral measure of relative TFP in any two countries a and b. Since we begin by measuring TFP compared to a common reference point (the geometric mean of all countries), these bilateral measures of relative TFP are transitive.

we see examples of loss of technological leadership as one economy 'leapfrogs' another (e.g. ISIC 35 and 381).[29] As discussed earlier, it is not the identity of the frontier country *per se* that is important in the econometric estimation, but the measure of distance from the technological frontier which we use to capture the potential for technology transfer.

Table 1 therefore also reports the sample mean and standard deviation of relative TFP (as measured by (14)) across countries for each industry in the years 1971, 1981, and 1990. For ease of interpretation we take the exponent of $RTFP_{ijt}$. This number is equal to unity for the frontier country and less than unity for non-frontier countries; the further away from unity (the smaller the number), the lower the level of TFP in economy i relative to the frontier.

In all industries except one (ISIC 39), average levels of relative TFP are higher in 1990 than 1971, and, in all industries except two (ISIC 32 and 36), the standard deviation is lower in 1990 than in 1971. This suggests σ-convergence in levels of relative TFP within OECD manufacturing industries during the sample period. This conclusion is confirmed in Figure 2, which graphs the sample standard deviation of relative TFP (not exponentiated) over time. In seven of the nine two-digit industries there is a marked downward trend in the standard deviation over time.

Insert Figure 1

Insert Figure 2

[29] For discussions of leapfrogging in technological leadership in a historical context, see Brezis *et al.* (1993) and Nelson and Wright (1992).

Table 1: Relative TFP and the identify of the frontier (skills adjustment and hours)

ISIC		1971	1981	1990			1971	1981	1990
31	First	Jap	Jap	USA	381	First	USA	Ger	Ger
	Second	Can	USA	Ita		Second	Ger	USA	USA
	Mean exp(RTFP)	0.65	0.69	0.77		Mean exp(RTFP)	0.78	0.85	0.88
	SD exp(RTFP)	0.20	0.18	0.17		SD exp(RTFP)	0.32	0.17	0.10
32	First	Fra	Dnk	Nld	382	First	Ger	Ger	USA
	Second	Swe	Fra	Fra		Second	USA	Ita	Fra
	Mean exp(RTFP)	0.72	0.77	0.78		Mean exp(RTFP)	0.88	0.90	0.93
	SD exp(RTFP)	0.18	0.17	0.19		SD exp(RTFP)	0.10	0.07	0.05
33	First	USA	USA	USA	383	First	USA	USA	USA
	Second	Ger	Ger	Swe		Second	Fra	Fra	Fra
	Mean exp(RTFP)	0.79	0.85	0.81		Mean exp(RTFP)	0.75	0.88	0.94
	SD exp(RTFP)	0.17	0.15	0.12		SD exp(RTFP)	0.31	0.15	0.06
34	First	USA	USA	Nld	384	First	USA	USA	USA
	Second	Fra	Fra	USA		Second	Ger	Ger	Ger
	Mean exp(RTFP)	0.62	0.68	0.80		Mean exp(RTFP)	0.71	0.88	0.95
	SD exp(RTFP)	0.20	0.18	0.15		SD exp(RTFP)	0.19	0.15	0.04
35	First	Jap	Ger	Ger	385	First	USA	Fra	Fra
	Second	Ger	Jap	Jap		Second	Ger	USA	USA
	Mean exp(RTFP)	0.55	0.70	0.79		Mean exp(RTFP)	0.67	0.82	0.87
	SD exp(RTFP)	0.23	0.20	0.19		SD exp(RTFP)	0.33	0.21	0.09
36	First	Can	Can	Nld	39	First	USA	Dnk	USA
	Second	Ger	Fra	Fra		Second	Dnk	USA	Ger
	Mean exp(RTFP)	0.78	0.85	0.86		Mean exp(RTFP)	0.77	0.71	0.68
	SD exp(RTFP)	0.14	0.11	0.12		SD exp(RTFP)	0.24	0.24	0.22
37	First	USA	Jap	Jap	30	First	USA	USA	Nld
	Second	UK	USA	Ita	(Total)	Second	Can	Nld	USA
	Mean exp(RTFP)	0.55	0.66	0.72		Mean exp(RTFP)	0.68	0.79	0.81
	SD exp(RTFP)	0.23	0.23	0.14		SD exp(RTFP)	0.15	0.14	0.13
38	First	USA	USA	Nld					
	Second	Ger	Ger	USA					
	Mean exp(RTFP)	0.54	0.71	0.76					
	SD exp(RTFP)	0.15	0.16	0.16					

31: Food, Beverages and Tobacco; 32: Textiles; 33: Wood; 34: Paper;35: Chemicals; 36: Non-metallic minerals; 37: Basic metals;38: Fabricated metals; 381: Metal products; 382: Agricultural and industrial machinery; 383: Electrical goods; 384: Transport equipment; 385: Instruments; 39: Other manufacturing; 30: total manufacturing.

Note: First is the frontier, second is the second highest TFP country; mean and S.D. of exp(RTFP) are the sample mean and standard deviation of the exponent of RTFP across countries. A value of the mean closer to unity corresponds to a higher average level of relative TFP.

At first sight, our finding of σ-convergence contrasts with the results in Bernard and Jones (1996a,b), who find that the majority of the convergence in economy-wide produc-

tivity amongst OECD countries during 1970-87 is driven by non-manufacturing industries. The measures of TFP used in this paper are more general than those employed by Bernard and Jones (1996a,b). We control for cross-country differences in the skill composition of the workforce, and, rather than assuming a Cobb-Douglas production function, we measure relative TFP using a superlative index number approach. The latter on its own is quantitatively important. If we recalculate our preferred measure of relative TFP (controlling for hours and the skill composition of the workforce), but assume a Cobb-Douglas production function with labour's exponent equal to the average share of labour compensation in value-added in each country-industry, we find a downward trend in the standard deviation of the log of relative TFP in only four of the nine two-digit manufacturing industries. Measuring relative TFP with a superlative index number consistent with the more general translog production technology strengthens the finding of productivity convergence in OECD manufacturing industries.[30] It should also be noted that the analysis of Bernard and Jones (1996a,b) is largely concerned with aggregate manufacturing and non-manufacturing sectors, and is therefore perfectly consistent with productivity convergence in individual manufacturing industries.

One of the striking features of Table 1 is the continued strength of the U.S. across a broad number of industries - despite the international diffusion of technologies, the U.S. has frequently managed to remain the technological leader. The analysis of Section 2 suggests that this is partly explained by the U.S.'s strong R&D performance in many industries. Table A3 in Appendix A reports average R&D intensities in each country-industry. It is clear that the leaders in TFP also tend to have high R&D intensities. To what extent this relationship is robust to further econometric controls is the subject of the next section.

4.3 The R&D Data

To measure R&D we use business expenditure on research and development (BERD). This includes all R&D performed by the business sector (from all sources of finance, including

[30]The standard deviation of labour shares across countries in each industry is relatively stable over time, showing a slight downward trend.

government subsidies) for each OECD country. The big advantage of this source of data is that considerable effort has been put in to making it comparable across countries and ISIC classification is common across countries. Data is available for the period 1974-94. The business sector is defined by the OECD to include state-owned manufacturing industries to make the sectors comparable across countries with different levels of public ownership.

This data has been widely used. It is described in some detail in Bloom, Griffith and Van Reenen (2001) and the micro data underlying the BERD for the UK has been described in Bloom and Griffith (2001). Table A3 in Appendix A reports average R&D intensities in each country-industry. Countries that are the technological frontier in a particiular industry (see Table 1) tend to also have higher R&D intensities.

One potential concern about this data is that the definition of "research and development" in the lower productivity countries could include the adoption costs of high tech capital goods. However, we think this is unlikely since only 10% or less of R&D is capital investment. In addition, any permanent cross-country differences in the composition of R&D spending are captured in the country-industry fixed effect.

5 Results

5.1 Main Results

As suggested in the discussion above, we are interested in exploring the two possible roles played by R&D - first as a direct determinant of the rate of innovation and secondly through increasing the absorptive capacity of the industry. We thus enter the R&D intensity in levels, to capture an effect on innovation, as well as interacted with the relative productivity term, which will capture an effect on the rate of technological transfer.

Column (1) of Table 2 examines the role played by technology transfer in determining rates of TFP growth, excluding both R&D terms. The relative TFP term enters negatively and is significant at conventional levels, indicating that within each industry the countries that are further behind the frontier experience higher rates of productivity growth. The

frontier TFP growth term is positive and statistically significant at conventional levels, as is consistent with a positive long-run relationship between country i TFP and frontier TFP. Controlling for unobserved heterogeneity using the within groups estimator increases (in absolute terms) the size of the estimated coefficient on relative TFP[31].

In column (2) of Table 2, we introduce the lagged level of R&D intensity, which enters positively and is statistically significant at conventional levels. Column (3) considers both the level of R&D and the interaction between R&D and relative TFP. The interaction term is expected to have a negative coefficient: the lower an economy's level of relative TFP (the more negative $RTFP_{ijt-1}$), the greater the potential for technologies to be transferred to the non-frontier country through R&D and the higher rates of productivity growth. From column (3), the estimated coefficient on the interaction term is indeed negative and statistically significant at the 10% level. The linear term remains positive and significant.

In columns (4) and (5), we adjust our TFP measure to take account of cross-country differences in the skill composition of the workforce and in hours worked. Column (4) exploits information on the share of production and non-production workers in employment and the wage bill in individual industries to control for labour quality. In column (5), we also control for cross-country differences in hours worked. The upshot of these results is that R&D appears to have both a linear effect (R&D generates innovations) and an interactive effect with relative TFP ($RTFP$) (R&D also spurs faster adoption of new technologies).

[31]If we re-estimate the specification in Column (1) of Table 2 dropping the fixed effects, the estimated coefficients (standard error) on relative TFP is -0.025 (0.005) and on frontier growth 0.138 (0.027). With OLS estimation there is evidence of serial correlation in the residuals (the LM test statistic is 2.246). Once we control for unobserved heterogeneity across country-industries, we find no evidence of serial correlation, as indicated by the LM test statistics reported at the base of Table 2.

Table 2: Impact of R&D and Human Capital on TFP growth

ΔTFP_{ijt}		(1)	(2)	(3)	(4)	(5)	(6)	(7)
ΔTFP_{Fjt}	β	0.146	0.137	0.136	0.134	0.124	0.121	0.119
		0.028	*0.027*	*0.027*	*0.027*	*0.030*	*0.030*	*0.030*
$RTFP_{ijt-1}$	-δ_1	-0.094	-0.097	-0.079	-0.079	-0.068	-0.024	-0.029
		0.014	*0.014*	*0.015*	*0.015*	*0.016*	*0.021*	*0.022*
R/Y_{ijt-1}	ρ_1	-	0.623	0.452	0.417	0.433	0.427	0.455
			0.168	*0.191*	*0.188*	*0.179*	*0.174*	*0.176*
$(RTFP * R/Y)_{ijt-1}$	-δ_2	-	-	-0.594	-0.632	-1.00	-0.815	-0.746
				0.335	*0.330*	*0.344*	*0.348*	*0.350*
H_{it-1}	ρ_2	-	-	-	-	-	0.225	0.251
							0.124	*0.124*
$(RTFP * H)_{it-1}$	-δ_3	-	-	-	-	-	-0.459	-0.424
							0.136	*0.139*
$IMPS/Y_{ijt-1}$	ρ_3	-	-	-	-	-	-	0.002
								0.011
$(RTFP * IMPS/Y)_{ijt-1}$	-δ_4	-	-	-	-	-	-	-0.065
								0.034
Serial correlation (LM)		0.296	0.373	0.374	0.376	0.185	0.318	0.348
(p-value)								
Skills adjustment					yes	yes	yes	yes
Hours adjustment						yes	yes	yes

Notes: sample contains 1801 observations from 1974-1990; numbers in italics are robust standard errors; all regression include full set of time dummies and full set of country-industry interactions (i.e. within groups estimator); observations are weighted using industry shares of total manufacturing employment; ΔTFP is growth in TFP; RTFP is relative level of TFP; R/Y is R&D intensity; H is human capital; IMPS is imports from the frontier; serial correlation is LM test for first order serial correlation, distributed N(0,1) under the null.

Although our baseline specification assumes that R&D is the critical factor in generating innovation and technology transfer, many authors have emphasised the roles of human capital and international trade in the growth process. The model presented earlier is therefore extended to incorporate these variables. Equation (9) becomes,

$$\begin{aligned}\triangle \ln A_{ijt} = \beta \triangle \ln A_{Fjt} - \delta_1 \ln \left(\frac{A_i}{A_F}\right)_{jt-1} - \delta_2 \left(\frac{R}{Y}\right)_{ijt-1} \ln \left(\frac{A_i}{A_F}\right)_{jt-1} \\ -\delta_3 H_{i,t-1} \ln \left(\frac{A_i}{A_F}\right)_{jt-1} - \delta_4 \left(\frac{IMPS}{Y}\right)_{ijt-1} \ln \left(\frac{A_i}{A_F}\right)_{jt-1} \\ +\rho_1 \left(\frac{R}{Y}\right)_{ijt-1} + \rho_2 H_{it-1} + \rho_3 \left(\frac{IMPS}{Y}\right)_{ijt-1} + u_{ijt}\end{aligned} \tag{15}$$

Our preferred measure of TFP weights numbers of production and non-production workers in a country-industry by their respective shares of the wage bill. In so far as any increased productivity of non-production workers is reflected in their wages (a private rate of return), it will therefore already be captured in our analysis. In this section, we are therefore concerned with estimating externalities to human capital accumulation. The existence of such externalities has been a frequent concern of the theoretical growth literature, including work on both *technological* externalities[32] and *pecuniary* externalities.[33] Since human capital's effect is thought to be an externality, we use country-level data on the percentage of the total population that has attained higher education from Barro and Lee (1994).[34] These data have the advantage of being available for all countries in our sample. We also investigate the use of industry-level educational attainment data from Machin and Van Reenen (1998), as discussed further below.

Column (6) of Table 2 presents the results including R&D and human capital. The estimated coefficients on the human capital level is positive and significant at the 10% level while the interaction is negative and significant at the 5% level. This provides evidence of positive externalities to higher educational attainment in the form of both a higher rate of innovation and more rapid technology transfer (the smaller a country's level of relative TFP, the greater the effect of higher educational attainment). The conclusions concerning the effects of R&D remain unchanged.

[32]See Lucas (1988), Nelson and Phelps (1966), and Benhabib and Spiegel (1994).

[33]See Acemoglu (1996) and Redding (1996). For microeconomic evidence on the complementarity between levels of human capital and the relative return to new technologies, see Bartel and Lichtenberg (1987).

[34]Higher education is a more appropriate variable than secondary education for OECD countries. Gemmell (1996), for example, finds that only this education variable is signigificant in OECD growth equations.

The role of the aggregate human capital variable is open to different interpretations.[35] To check the robustness of our results we did several things. For six countries we have industry-level educational variables which we used instead of the aggregate variables. The human capital terms were correctly signed but only the linear term was significant at the 10% level.[36] This could be due to sample size, but it is suggestive of human capital externalities operating at the country-wide level.

The role of international trade is stressed in both the cross-country growth literature and work on international R&D knowledge spillovers.[37] The theoretical literature suggests a variety of mechanisms by which trade may affect productivity growth (e.g. spillovers of technology from the reverse engineering of imported goods, increased product market competition, and larger market size), and there are a number of ways to introduce international trade in the model. We take a simple and intuitive approach that, at the same time, is sufficiently general to allow trade to affect both innovation and technology transfer. The OECD bilateral trade database provides information for each industry in each country on the source of imports from trading partners in the OECD. Using these data, we construct measures of import penetration for each industry in each country. Our preferred measure uses imports from the frontier, although we also experimented with using imports from the whole world, imports from other OECD countries excluding the frontier, and imports from non-OECD countries.[38] International trade flows are scaled by output and we include both

[35]See Krueger and Lindahl (1998) and Topel (2000) for a critical discussion and recent evidence. See also Berman (2000) for an interpretation in terms of skill-biased technological change.

[36]The specification in column (6) of Table 2 was re-estimated using the industry-level education data. The estimated coefficients (*standard errors*) on the linear and interaction education were 0.394 (*0.204*) and -0.317 (*0.530*) respectively. We also experimented with other non-linearities with human capital, but none of tehs eterms were significant at conventional levels.

[37]Examples of cross-country growth studies include Edwards (1998), Frankel and Romer (1999), and Harrison (1996), while influential studies of trade and international R&D knowledge spillovers include Coe and Helpman (1995), Coe, Helpman and Hoffmaister (1997), and Keller (1997, 1999).

[38]The results using imports from the whole world (not shown) are very similar to those with imports from the frontier, suggesting that it is openness *per se* which fosters technology transfer and not whether a country is directly importing from the most advanced nations. The results are weakest for imports from non-OECD countries, which does not seem consistent with the arguments of Wood (1994), who claims that trade with developing countries has resulted in large amounts of induced innovation (and so lowered the demand for less skilled workers).

a level and interaction term for import penetration.

In Column (7) of Table 2, we include information on R&D, human capital, and international trade. The magnitude and statistical significance of the coefficients on the R&D and human capital terms remain largely unchanged. The import level term is positively signed, although the estimated coefficient is small in magnitude, and statistically insignificant at conventional levels. The import interaction term is negatively signed and statistically significant at the 10% level. Thus, increased trade with the frontier tends to have a (weakly) positive effect on rates of productivity growth through the speed of technology transfer, but not through rates of innovation.[39]

5.2 Economic Importance and Policy Implications

We have found that R&D and human capital have positive and statistically significant effects on rates of TFP growth through both innovation and technology transfer. How economically important are these effects? The estimated coefficients in Table 2 are sometimes hard to interpret in a direct and intuitive way, so in this Section, we consider the quantitative importance and the implications for policy. Since the import interaction term is only weakly statistically significant, we concentrate on the results with R&D and human capital (column (6) in Table 2). In principle, the model can be used to evaluate the effect of each variable in each manufacturing industry. In the interests of brevity, we focus on the implications for total manufacturing.

In Section 2, we saw that the estimated coefficient on the R&D intensity can be interpreted as a social rate of return. The presence of the interaction term implies that R&D's full rate of return to R&D depends upon both innovation and technology transfer: $\hat{\rho}_R \equiv \hat{\rho}_1 - \hat{\delta}_2 . \ln(A_i/A_F)_{ijt-1}$. Our estimate of R&D's social rate of return from *innovation*

[39]Some authors have suggested that more recent investment in physical capital may be a way of incorporating international technology transfer. Although our model attempts to capture this through the measurement of capital in TFP, we also experimented with including the level of investment/value added and its interaction with relative TFP. Including these variables in a specification like column (6) of Table 2 yields the following coefficients (standard error): level of I/Y(t-1) -0.116 (0.040), interaction of (I/Y*RTFP)t-1 -0.062 (0.033), while the R&D terms do not differ significantly, with the level of R&D(t-1) 0.589 (0.204) and the Interaction -0.711 (0.368). The estimated R&D effects remain of a similar magnitude and statistically significant.

($\hat{\rho}_1$) is about 43%. This is close to existing estimates in studies of R&D and productivity.[40] Many of these studies have been undertaken using US data, and the US is typically the frontier in our dataset. Thus, the US rate of return to R&D should largely be due to innovation.

R&D's full rate of return varies with a country's distance from the technological frontier. Column (1) of Table 3 reports the exponent of average relative TFP_{t-1} in total manufacturing during 1974-90 in each of the 12 countries in our dataset. This number is 1 for the frontier and less than 1 for all non-frontier countries. Column (2) evaluates the full rate of return to R&D (from both innovation and absorptive capacity) using the average relative TFP reported in column (1). The US social rate of return to R&D is indeed due almost entirely to innovation (a total rate of return of 0.432, compared to a rate of return from innovation alone of 0.427). In contrast, with average relative TFP just over 50% of the level in the frontier, less than half of the social rate of return to R&D in Finland (0.952) is due to innovation - absorptive capacity is quantitatively more important.

[40]For example, Sveikauses (1981) estimates a social rate of return to R&D of 50%, while Griliches and Lichtenberg (1984) estimate a social rate of return to R&D of 41-62%. See Jones and Williams (1998) for a discussion of existing estimates of the social rate of return to R&D and their relationship to the endogenous growth literature.

Table 3: Quantifying the effects of R&D and Human Capital

		Innovation + Absorptive Capacity	
Country	(1)	(2)	(3)
		R&D	Human Capital
Country	$\overline{RTFP}$	$\hat{\rho}_1 - \hat{\delta}_2 \ln(\overline{RTFP})$	$\hat{\rho}_2 - \hat{\delta}_3 \ln(\overline{RTFP})$
		$\hat{\rho}_1 = 0.427$	$\hat{\rho}_2 = 0.225$
		-$\hat{\delta}_2 = -0.815$	-$\hat{\delta}_3 = -0.459$
Canada	0.826	0.583	0.313
Denmark	0.728	0.686	0.371
Finland	0.525	0.952	0.521
France	0.849	0.560	0.300
Germany	0.901	0.512	0.273
Italy	0.696	0.722	0.391
Japan	0.703	0.714	0.387
Netherlands	0.905	0.508	0.271
Norway	0.663	0.762	0.414
Sweden	0.726	0.688	0.372
United Kingdom	0.626	0.809	0.440
United States	0.994	0.432	0.228

Notes: $RTFP$ is the average value of lagged relative TFP in total manufacturing during 1974-1990; the parameters reported above are those estimated in column (6) of Table 2.

One important conclusion from this analysis is that many existing studies, in so far as they are based on US data (a country which is typically the frontier), will tend to underestimate the full social rate of return to R&D. In non-frontier countries, R&D may generate TFP growth from both innovation and technology transfer. This conclusion receives independent support from the results of Eaton *et al.* (1998). The latter calibrate a computable general equilibrium model of endogenous innovation and growth to economy-wide data from 21 OECD countries. With the exception of Portugal, research productivity in all other OECD countries is found to higher than in the U.S. If the social rate of return to R&D is higher in non-frontier countries, this of course raises the question why they do not undertake more R&D. One answer may be that there are larger differences between private and social rates of return - if some of the technology transfer induced by R&D activity takes the form of an externality (as indeed is suggested by the human capital results) it will not be internalised by private sector agents. The explanation provided by Eaton *et al.* (1998) is that research

incentives are lower in other OECD countries due to a smaller market size. Market failures such as the underdevelopment of financial markets and government policies provide are alternative explanations.

A second conclusion of the analysis is that it is important to draw a distinction between the social rate of return to R&D at the *national* and the *supra-national* levels. In the theoretical model presented in Section 2, an increase in R&D in the frontier raises the steady-state rate of TFP growth in *all other countries* (in steady-state, TFP in all countries grows at the same rate in a particular industry, equal to TFP growth in the frontier). Thus, although *national* social rates of return to R&D are higher in non-frontier countries, there is an important *supra-national* externality to R&D undertaken in the frontier. Depending on the balance between this supra-national externality and R&D role's in promoting absorptive capacity, it could be welfare improving for the world as a whole to relocate R&D from individual non-frontier countries to the frontier.

A similar analysis is undertaken in column (3) of Table 3 for the effects of human capital. The model predicts that the social rate of return to increased educational attainment is higher in countries further from the technological frontier ($\hat{\rho}_H \equiv \hat{\rho}_2 - \hat{\delta}_3 . \ln(A_i/A_F)_{ijt-1}$). Thus, in the US, the full effect of human capital on TFP growth ($\hat{\rho}_H = 0.228$) is almost entirely due to innovation ($\hat{\rho}_2 = 0.225$). In Finland, whose average relative TFP is just over 50% of the frontier's, less than half of human capital's full effect ($\hat{\rho}_H = 0.521$) is due to innovation - absorptive capacity is again quantitatively more important. While the endogenous growth literature has emphasised human capital externalities for innovation,[41] our empirical results suggest that there are statistically significant and quantitatively important human capital externalities in the process of technology transfer. This is consistent with a theoretical literature dating back to the work of Nelson and Phelps (1966) and with the empirical results using aggregate whole-economy data in Benhabib and Spiegel (1994).

[41] See, in particular, Lucas (1988).

6 Robustness of Results

There a number of concerns about the results presented above. In this section we consider the robustness of our results to the following concerns: (i) bias due to measurement error; (ii) non-linearities and diminishing returns to R&D, (iii) sensitivity to the definition of the frontier; (iv) parameter heterogeneity; and (v) cross-industry spillovers.

6.1 Measurement error in TFP

Our first concern is with measurement error. If we measure TFP with error then the weak exogeneity assumption will not be valid. The left hand side of our regression is measured TFP growth ($\ln(A_{ijt}/A_{ijt-1})$) while the right hand side contains measured relative TFP ($\ln(A_{ijt-1}/A_{Fjt-1})$). If A_{ijt}, A_{ijt-1}, and A_{Fjt-1} are each subject to errors of measurement, the OLS estimate of the coefficient on relative TFP will be biased. To deal with this potential problem we use IV estimation. In the absence of serial correlation (conditional on the country-industry fixed effect and the other covariates), longer lagged values of relative TFP are valid instruments. In columns (1) to (3) of Table 4 we replicate the results from columns (5) to (7) of Table 2 but instrument the relative TFP term with lags of itself $(t-2)$ and $(t-3)$. The results are very similar to those presented in Table 2.[42]

A complementary approach uses data on some of the variables suggested as sources of measurement error in the TFP literature. Column (4) presents estimation results using a measure of relative TFP that controls for cross-country and cross-industry variation in the degree of imperfect competition using data on the markup of price over marginal cost in individual country-industries. In Column (5), we present results using a measure of relative TFP that controls for both country-industry variation in the degree of imperfect competition

[42]We considered two tests of the validity of the instruments in addition to the serial correlation tests. First, the Sargan test at the base of the columns reports the correlation of the residuals with the instruments. Second, we consider an F-test of the excluded instruments in the reduced forms (IV will be biased towards OLS if the overidentifying instruments are weakly correlated with the endogenous variables). In fact the excluded instruments were always highly significant. For example, in column (1) of Table 4 the P-value for an F-test of the significance of $RTFP_{ijt-2}, RTFP_{ijt-3}, (RTFP_{ijt-2} * R/Y_{ijt-1}), (RTFP_{ijt-3} * R/Y_{ijt-1})$ was 0.00.

and country-industry-time variation in capacity utilisation.[43]

In both cases, the conclusions from the IV estimation are confirmed, and the finding of a 'second face' of R&D activity is robust. The coefficients on the R&D level and interaction terms remain of a similar magnitude and statistically significant at the 5% level. The human capital interaction is negatively signed and statistically significant, suggesting a role for human capital in the process of technology transfer. Neither the international trade level nor the interaction term is statistically significant at conventional critical values.[44]

6.2 Non-linearities and diminishing returns to R&D

We have interpreted the interaction term between R&D and relative TFP as indication of technology transfer associated with R&D. An alternative interpretation, however, is that there are sharply diminishing returns to R&D and that countries further behind the frontier have a higher rate of return simply because they perform less R&D and are therefore higher up the marginal revenue productivity curve. The empirical implication of this alternative story is that higher order terms in R&D intensity should be included in our specifications and this should drive out the interaction of R&D with relative TFP. We tested for such non-linearities in the R&D term and found that these higher order terms in R&D were always insignificant. Column (6) shows a representative example; we include a squared R&D intensity term. Although it is negative (suggesting diminishing returns) it is insignificant. More importantly the interaction terms with relative TFP (both of human capital and R&D) were basically unchanged by the addition of this variable.

[43] See Appendix A for further details concerning the construction of these measures.

[44] We also experimented with using data on industry-specific Purchasing Power Parities (PPPs). Once again, the conclusions were essentially unchanged: see Griffith, Redding and Van Reenen (2000) for further details.

Table 4: Robustness of the main results

ΔTFP_{ijt}	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Estimation	IV	IV	IV	OLS	OLS	OLS	OLS
ΔTFP_{Fjt}	0.130	0.128	0.125	0.110	0.090	0.118	0.057
	0.031	*0.031*	*0.031*	*0.029*	*0.031*	*0.030*	*0.034*
$RTFP_{ijt-1}$	-0.072	-0.034	-0.037	-0.015	-0.023	-0.030	-0.071
	0.020	*0.025*	*0.025*	*0.022*	*0.020*	*0.020*	*0.018*
R/Y_{ijt-1}	0.382	0.383	0.417	0.460	0.313	0.749	0.390
	0.189	*0.183*	*0.187*	*0.176*	*0.155*	*0.331*	*0.178*
$(R/Y_{ijt-1})^2$						-1.318	
						1.238	
$(RTFP * R/Y)_{ijt-1}$	-1.345	-1.14	-1.05	-0.904	-0.938	-0.704	-1.207
	0.398	*0.404*	*0.408*	*0.346*	*0.339*	*0.350*	*0.385*
H_{it-1}	-	0.237	0.264	0.245	0.197	0.218	
		0.124	*0.127*	*0.130*	*0.120*	*0.123*	
$(RTFP * H)_{ijt-1}$	-	-0.432	-0.413	-0.409	-0.317	-0.448	
		0.176	*0.179*	*0.143*	*0.140*	*0.100*	
$IMPS/Y_{ijt-1}$	-	-	-0.016	-0.004	0.012		
			0.108	*0.027*	*0.032*		
$(RTFP * IMPS/Y_{ijt-1}$	-	-	-0.093	-0.046	-0.041		
			0.193	0.045	0.047		
Serial Correlation (p-value)	0.969	1.060	1.074	0.452	0.581	0.338	1.033
Sargan (p-value)	0.072	0.086	0.105	-	-	-	
Adjustments to TFP	s,h	s,h	s,h	s,h,m	s,h,m,c	sh	sh
Definition of Frontier	ONE	ONE	ONE	ONE	ONE	ONE	TWO

Notes: sample contains 1801 observations from 1974-1990; numbers in italics coefficients are robust standard errors; all regressions include full set of time dummies and full set of country-industry interactions (i.e. within groups estimator); observations are weighted using industry shares of total manufacturing employment; ΔTFP is growth in TFP; R/Y is R&D divided by value added; H is human capital; IMPS is imports from the frontier; serial correlation is LM test for first order serial correlation, distributed N(0,1) under null; Sargan is test for validity of overidentifying restrictions; TFP adjustments are s: skills, h: hours, m: markup and c: capacity utilisation (see Appendix for details); instruments include in all columns: $\Delta TFP_{Fjt}, RTFP_{ijt-2}, RTFP_{ijt-3}, R/Y_{ijt-1}, (RTFP_{ijt-2} * R/Y_{ijt-1}), (RTFP_{ijt-3} * R/Y_{ijt-1})$; plus in column (2) $H_{ijt-1}, (RTFP_{ijt-2} * H_{ijt-1}), (RTFP_{ijt-3} * H_{ijt-1})$; plus in column (3) $IMP_{ijt-2}, IMP_{ijt-3}, (RTFP_{ijt-2} * IMP_{ijt-2}), (RTFP_{ijt-3} * H_{ijt-3})$;RTFP is the realtive level of the industry-country's TFP: ONE indicates that the potential for technology transfer country is measured by TFP relative to the frontier; TWO indicates that the potential for technology transfer captured by TFP relative to the average of the two countries with the highest TFP levels

6.3 The Definition of the Frontier

Now sensitive are our results to the definition of the frontier? In our model what matters for the regressions is not the identity of the frontier *per se*, but the measure of distance from the technological frontier which we use to capture the potential for technology transfer. We have already shown that our results are robust to a series of different adjustments to TFP measures. In column (7) of Table 4 we also report results using the average of the top two countries as an indicator of the frontier and the results are similar to column (5) of Table 2.

6.4 Allowing parameters to vary across all industry-country pairs

The specification in equation (15) allows the coefficient on the gap to vary with R&D, human capital, and international trade. This places a particular economic structure on parameter heterogeneity. We now consider the implications of allowing for more general forms of heterogeneity.[45] Table 5 reports the results from specifications which allow the coefficients to vary across each of the 113 country-industry cross-section units. To provide a benchmark against which to compare the results of the heterogeneous coefficient estimation, column (1) of Table 5 estimates the specification in column (6) of Table 2 but without the terms interacted with relative TFP. The interaction terms are excluded, because they already constitute a method of allowing the coefficients on R&D and human capital to vary across industries. In the heterogeneous coefficient estimation we wish to allow the coefficients on these variables to vary across country-industries (as dictated by the data alone). We report medians as the means can be sensitive to one or two extreme estimated values.

In Table 5, we report some results of these experiments.[46] The estimates in column (1) and (2) are similar for both the frontier growth and TFP gap terms. However, the median estimated coefficients on the R&D level is quite different from those estimated imposing parameter homogeneity. This is precisely what would be expected from our theoretical model

[45] See, for example, Pesaran and Smith (1995).

[46] In each row of column (2) we estimate the same equation as column (1) but allow the variable of interest to be interacted with the fixed effects, keeping the coefficients on the other variables fixed.

and preferred specification - we expect the impact of R&D to be higher in those countries that have lower levels of relative TFP and are farther from the technological frontier. In order to investigate whether this is the case, we split the sample by the median value of relative TFP into those country-industries that are far from the frontier ('large gap') and those that are closer to the frontier ('small gap').[47] These results reveal that the effects of R&D and human capital are more important for those countries that are far from the technological frontier. In summary, this corroborates our qualitative findings from the more parsimonious models of Table 2.

Table 5: Heterogeneity of Coefficients

	(1)	(2)	(3)	(4)
		Heterogeneous coefficient (median)		
	Pooled Coefficient	Overall	Small Gap	Large Gap
ΔTFP_{Fjt}	0.123	0.093	-	-
$RTFP_{ijt-1}$	-0.098	-0.116	-	-
$(R/Y)_{ijt-1}$	0.583	1.13	0.168	2.42
H_{it-1}	0.350	0.387	-0.096	0.883

Notes: Country-industry fixed effects and common time effects are included in all specifications. Column (1) pooled coefficient is the estimated coefficient from a model including $RTFP$, frontier growth, human capital, imports and R&D but with no interaction effects; Columns (2)-(4) are from model in column (1), but extended to allow coefficients vary across each country-industry pair (113 interactions). Column (2) is median estimated parameter across all observations (in 1980). Column (3) is median for observations where $RTFP$ is below its 1980 median ($RTFP < -0.352$ log points). Column (4) is median for observations where $RTFP$ is above its 1980 median ($RTFP \geq -0.352$ log points).

6.5 Domestic Inter-industry spillovers

Our final concern is that technology can also be transferred across industries as well. This conduit of transfer has been investigated more extensively in the literature.[48] The basic problem is constructing the appropriate "knowledge flow matrix", which specifies *ex ante* who gains knowledge from whom.[49] In the empirical application here our main interest is in

[47] We split the sample based on the median value of relative TFP in 1980. Similar findings emerge from splitting the sample on the median value of relative TFP across all time periods etc.

[48] See Griliches (1992) for a survey.

[49] Different possibilities include input-output matrices, mappings between the users and suppliers of innovations, technology classes from patent statistics or patent citation information. See Jaffe (1986) for one of

examining international spillovers at the industry level, an area where there has been relatively little empirical work. Our main aim is to obtain robust estimates of the coefficients in (4). A simple test is to include economy-wide R&D intensity and its interaction as a specification test. This assumes that all industries are equally capable of gaining spillovers from all others - a restricted form of the domestic inter-industry spillover matrix (international inter-industry flows being captured by the time dummies). Both variables took their expected signs but were insignificant at conventional levels. The industry-specific terms dominated over their more aggregate counterparts.[50] Given the lack of consensus for the appropriate matrix, we leave a more sophisticated treatment of inter-industry spillovers for future work.

7 Conclusions

This paper has produced econometric evidence on the importance of the "two faces of R&D" by examining the determinants of productivity growth in a panel of industries across twelve OECD countries. R&D stimulates growth directly through innovation and also indirectly through technology transfer. Thus R&D has played a role in the convergence of TFP levels within industries across OECD countries. This result was robust to a variety of tests including measuring TFP in a number of different ways. We also identified a role for human capital in stimulating innovation and absorptive capacity. By contrast, trade had a statistically weak effect on productivity. The R&D and human capital effects were shown to be quantitatively important as well as statistically significant.

An implication of the results is that the social returns to investing in R&D and human capital are underestimated in studies which focus solely on the U.S. economy, since the U.S. is the technological frontier for a large number of industries. There is also an important spillover at the world level from frontier to non-frontier countries. As a result of technology

the most convincing analyses.

[50]For example, in the context of column (5) of Table 2 the coefficient (*standard error*) on aggregate linear R&D intensity was 0.435 (*0.376)*, coefficent on the interaction was -0.656 (*0.487*). The industry R&D intensity variable took a coefficient (*standard error*) of 0.389 (*0.172*) and the industry R&D interaction -0.772 (*0.357*).

transfer, an increase in frontier R&D not only raises the steady-state rate of TFP growth in the frontier, but also raises steady-state TFP growth in non-frontier countries.

One important question is why non-frontier countries do not invest more in R&D since the social return is higher than in the frontier? As the incentive to invest in R&D is determined by the private return and not the social return, it may be the case that R&D is held back in many non-frontier countries by under-development of financial markets or inappropriate government policies. A future research agenda should be to investigate these issues, through using firm-level data across a number of countries to estimate private and social rates of return in a framework which allows for the two faces of R&D.

Another avenue for future work would be to extend our framework to incorporate inter-industry technology transfers. Despite the need for these further extensions, we believe the methods presented here provide a tractable and intuitive approach to understanding productivity dynamics across OECD countries and industries. The emphasis on human capital and R&D in modern growth theory is well placed.

Appendix A: Data Appendix

A.1. Data Sources

We constructed our panel dataset by combining several sources. Our sample consists of twelve countries over the period 1970-1992. For some of the countries, information is available for nine two-digit industries (ISIC 31-39), while for others ISIC 38 is additionally broken down into five three-digit industries. Where the more disaggregated information is available for the three-digit industries we use it. At the same time, careful attention is paid to the robustness of the results to alternative samples of countries and industries. After cleaning and deleting missing values, the distribution of observations across countries and industries in our full sample is as displayed in Table 1.

Table A.1: Sample size for TFP data by industry and country, 1970-1992

ISIC	Can	Dnk	Fin	Fra	Ger	Ita	Jap	Net	Nor	Swe	UK	USA	Total
31	23	23	23	23	23	23	23	8	22	23	23	23	260
32	23	23	23	23	23	23	23	8	22	23	23	23	260
33	23	23	23	23	23	-	-	-	22	23	-	23	183
34	23	23	23	23	23	-	23	8	22	23	23	23	237
35	23	23	23	23	23	23	23	8	22	23	23	23	260
36	23	23	23	23	23	23	23	8	-	23	21	23	236
37	23	23	23	23	23	23	23	8	22	23	20	23	257
38	23	23	23	-	-	-	23	8	-	23	23	-	146
381	-	-	-	22	23	23	-	-	-	-	-	23	91
382	-	-	-	22	23	23	-	-	-	-	-	23	91
383	-	-	-	22	23	23	-	-	-	-	-	23	91
384	-	-	-	22	23	23	-	-	-	-	-	23	91
385	-	-	-	22	23	23	-	-	-	-	-	23	91
39	23	23	23	-	23	23	23	-	-	-	23	23	184
Total	207	207	207	271	299	253	184	56	132	184	179	299	2478

31: Food, Beverages and Tobacco; 32: Textiles; 33: Wood; 34: Paper;35: Chemicals; 36: Non-metallic minerals; 37: Basic metals;38: Fabricated metals; 381: Metal products; 382: Agricultural and industrial machinery; 383: Electrical goods; 384: Transport equipment; 385: Instruments; 39: Other manufacturing.

OECD International Sectoral Database (ISDB): data on real value-added, real capital stock, employment, hours worked, and share of labour compensation in value-added. These data are available for the 12 OECD countries and 15 industries listed in Table 1. The industrial classification used is the International Standard Industrial Classification (ISIC). Information is available for the period 1970-94. However, missing values for a number of countries during the final two years and the availability of R&D data at the beginning of the period mean that the regression sample is constrained to 1974-92.

OECD ANBERD/ANRSE (Research and Development in Industry: Expenditure and Researchers, Scientists and Engineers) Database: data on Business Enterprise Expenditure on Research and Development (BERD) by industry for each OECD country. The same ISIC classification is used as in the ISDB data, and information is avail-

able for the period 1974-94. R&D is performed by the business sector, but includes all sources of funding (industry and business, domestic and overseas). The business sector is defined by the OECD to include state-owned manufacturing industries to make the sectors comparable across countries with different levels of public ownership.

OECD Bilateral Trade Database (BTD): data on the value of each OECD country's bilateral imports from all other OECD countries, 15 partner countries, and the whole world. The data are available for each of the ISIC manufacturing industries listed in Table 1 during 1970-94. The 15 partner countries are: Argentina, Brazil, China, Czech and Slovak Republics, Hong Kong, Hungary, India, Indonesia, Malaysia, Mexico, Philippines, Singapore, South Korea, Taiwan, and Thailand. For each country in our sample, these data were used to construct (i) imports from anywhere in the world, (ii) imports from the frontier, and (iii) imports from non-OECD countries.

United Nations General Industrial Statistics Database (UNISD): data on the numbers and wage bills of non-production and production workers 1970-90. This is a crude distinction, but is the only one available consistently across a large range of industries and countries over time. It has been analyzed extensively by other authors (e.g. Berman, Bound and Machin, 1998) who have found the occupational spilt highly correlated with alternative measures of human capital (such as education) The industrial classification is again the same ISIC classification as in the ISDB data. Information is available for the following countries: Canada, Denmark, Finland, Japan, Sweden, United Kingdom, and United States. For all other countries, we use the mean employment and wage bill shares across countries in a particular industry and year. The regression results are similar if we instead use the employment and wage bill share in the United States in a particular industry and year for those countries where data is not available.

Industry-specific Mark-ups: data on industry-specific mark-ups of product prices over marginal costs for 36 three and four-digit ISIC manufacturing industries are taken from Martins *et al.* (1996). These are estimated for the period 1970-92 using Roeger's (1995) methodology, which builds on Hall (1988). Data are available for the 12 OECD countries listed in Table 1. We aggregate up to the two and three-digit ISIC manufacturing industries listed in Table 1 using shares of current-price value-added.

Educational attainment: we use the 'percentage of higher school attained in the total population' variable from Barro and Lee (1994). These data are whole economy and are available for the 12 OECD countries listed in Table 1 at five-yearly intervals during 1960-85. Following Feenstra et al. (1997) and Harrigan (1997), we interpolate between non-missing observations and extrapolate forward in time. For the industry specific education proportions we use the data gathered in Machin and Van Reenen (1998) which is aggregated from individual level data sources (Such as the CPS in the U.S.). These numbers are available only for France, Germany, Japan, Sweden, U.K., and the U.S.

A.2. TFP Measures

Much attention has been paid to how to measure TFP accurately and how to obtain comparable numbers across countries. To tackle this problem we try and measure TFP in a number

of ways and test whether our results are robust to the various corrections. We do four main types of corrections: (a) adjustments to the measure of labour inputs for differences in hours worked and skill levels, (b) adjustments to factor shares due to imperfect competition, (c) adjustments to the capital stock for differences in capacity utilization, and (d) the use of manufacturing-industry-specific rather than economy-wide PPPs. Our baseline measures are described in Section 4, and were constructing using the data as reported in the ISDB.

A.2.1. Adjusting labour input for differences in hours and skills

We make a variety of corrections to the measure of labour input in the empirical analysis. Our base measure is numbers employed in industry j of economy i. We then adjust this by average annual hours actually worked per person in employment (from the ISDB). This is an economy-wide adjustment. Our third and preferred measure of labour input controls for differences in the quality of labour inputs. Employment in each country-industry-year is sub-divided into the number of production and non-production workers using UN data on the proportion of each category of worker. Following Harrigan (1999) and Jorgenson and Fraumeni (1992), aggregate labour input can be expressed as a translog index of the two types of labour,

$$L_{ijt} = (h_{ijt})^{s_{ijt}}.(u_{ijt})^{1-s_{ijt}}$$

where h_{ijt} denotes the number of non-production workers, u_{ijt} denotes the number of production workers, and s_{ijt} is the share of non-production workers in the wage bill. In making this adjustment, we use country-industry data on h_{ijt} and s_{ijt} where it is available (for Canada, Denmark, Finland, Japan, Sweden, United Kingdom, and United States) and mean values of h_{ijt} and s_{ijt} across these countries in each industry where the data not available. Table B1 presents the data on rates of TFP growth, controlling for cross-country differences in hours and skills, to compare with the figures reported in Table 2 in the main text.

A.2.2. Adjusting for markups

We allow for imperfect competition with country-industry specific markups using estimates from Martins, Scarpetta and Pilat (1996). These implement Roeger (1995)'s method (building upon Hall (1988)) using the OECD Stan data. The labour share parameter α_{ijt} in the superlative indices of TFP growth and relative TFP ((11) and (13)) is replaced by,

$$\widetilde{\alpha}_{ijt} = \mu_{ij}\alpha_{ijt}.$$

where μ_{ij} is the country-industry specific mark-up. The markup estimates in Martins *et. al* (1996) are aggregated up to the level of disaggregation in the ISDB data using value-added shares. Where markups were not available for an entire 2-digit industry, we used the mean of the markup in other countries for that industry.

A.2.3. Adjusting capital for capacity utilization

We adjust for the fact that countries may have different economic cycles, and that during down turns capital may not be fully used while during booms it may be over used. We

construct a measure of capacity utilization.. by estimating a smoothed output series, $\widehat{Y}_{ijt}$, which is predicted from a regression

$$Y_{ijt} = \delta_{ij} + t_t$$

where t_t is a time trend. Adjusted capital input is then given by,

$$(K * CU)_{ijt} = K_{ijt} * \left(1 + \frac{Y_{ijt} - \widehat{Y}_{ijt}}{\widehat{Y}_{ijt}}\right).$$

A.3 Descriptive Statistics

Our preferred measure is the one that corrects for hours worked and skills levels (we are less confident about our other adjustments but use them to check the robustness of our results). In Table A1, the mean annual growth rates of our preferred measure are given by country-industry. It can be seen that there is considerable heterogeneity in rates of TFP growth across both countries and manufacturing industries.

Table A.2: Mean annual growth rate of TFP (hours and skills), 1971-1990 (%)

ISIC	Can	Dnk	Fin	Fra	Ger	Ita	Jap	Net	Nor	Swe	UK	USA
31	0.3	3.4	1.4	1.2	1.0	1.5	-2.0	2.8	-0.4	0.8	1.5	0.9
32	3.4	3.2	2.7	2.4	3.0	3.5	3.4	1.4	3.4	2.9	2.7	3.4
33	3.4	1.9	3.6	3.3	1.6	-	-	-	-0.2	2.0	-	1.6
34	0.7	1.1	2.6	1.0	2.0	-	1.7	0.4	1.4	1.5	1.8	0.2
35	2.8	3.1	1.4	1.9	1.3	7.3	-0.7	0.9	1.9	2.1	2.9	1.7
36	1.4	-0.1	2.1	2.9	2.4	3.7	0.6	1.5	-	2.4	2.2	1.4
37	0.6	4.2	3.1	2.3	3.0	0.8	-0.0	-0.0	4.0	3.7	4.1	-0.4
38	3.2	1.7	3.8	-	-	-	4.9	1.8	-	2.5	2.7	-
381	-	-	-	1.9	1.4	5.5	-	-	-	-	-	1.1
382	-	-	-	2.7	1.2	1.1	-	-	-	-	-	1.9
383	-	-	-	3.8	4.0	9.1	-	-	-	-	-	3.6
384	-	-	-	2.5	2.2	1.9	-	-	-	-	-	0.9
385	-	-	-	4.1	2.7	8.5	-	-	-	-	-	2.0
39	1.7	0.5	1.9	-	0.7	1.8	1.5	-	-	-	2.0	2.1
30 (Total)	1.4	2.3	2.8	2.6	2.2	3.7	2.0	3.2	1.6	2.2	2.7	1.5

31: Food, Beverages and Tobacco; 32: Textiles; 33: Wood; 34: Paper;35: Chemicals; 36: Non-metallic minerals; 37: Basic metals;38: Fabricated metals; 381: Metal products; 382: Agricultural and industrial machinery; 383: Electrical goods; 384: Transport equipment; 385: Instruments; 39: Other manufacturing.

Table A2 tabulates average R&D intensities by industry. It is clear that the leaders in TFP also tend to have high R&D intensities.

Table A.3: Average R&D intensity, 1974-1992

ISIC	Can	Dnk	Fin	Fra	Ger	Ita	Jap	Net	Nor	Swe	UK	USA
31	0.5	1.0	1.4	0.6	0.4	0.2	1.3	2.2	1.0	1.8	1.3	1.1
32	0.5	0.3	0.6	0.4	0.5	0.0	2.1	0.7	0.8	0.8	0.6	0.4
33	0.3	0.3	0.7	0.2	0.5	-	-	-	0.4	0.3	-	0.5
34	0.7	0.1	1.4	0.2	0.4	-	1.7	0.2	0.8	1.7	0.3	0.8
35	4.4	6.6	5.7	6.2	7.1	4.6	9.5	8.1	4.7	9.2	8.4	8.7
36	0.5	1.6	1.7	1.5	1.3	0.1	3.6	0.5	-	1.8	1.5	2.6
37	2.2	1.9	3.2	2.0	1.3	0.9	3.4	2.5	4.6	4.2	0.9	1.8
38	5.3	4.2	5.7	-	-	-	7.7	10.2	-	10.9	10.7	-
381	-	-	-	0.6	1.3	0.4	-	-	-	-	-	1.3
382	-	-	-	2.5	5.2	1.1	-	-	-	-	-	2.6
383	-	-	-	13.7	12.4	6.1	-	-	-	-	-	18.1
384	-	-	-	13.9	10.8	8.5	-	-	-	-	-	25.2
385	-	-	-	1.9	3.0	1.0	-	-	-	-	-	11.4
39	0.7	14.7	0.4	-	0.9	0.8	0.3	-	-	-	1.3	3.1
Total	2.6	3.0	3.1	4.9	5.1	2.0	5.2	5.1	3.7	6.7	5.5	7.9

31: Food, Beverages and Tobacco; 32: Textiles; 33: Wood; 34: Paper;35: Chemicals; 36: Non-metallic minerals; 37: Basic metals;38: Fabricated metals; 381: Metal products; 382: Agricultural and industrial machinery; 383: Electrical goods; 384: Transport equipment; 385: Instruments; 39: Other manufacturing; Total: ISIC 30.

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