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Discussion paper

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in a panel of OECD industries

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 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 document that there has been convergence of TFP within a panel of industries across thirteen OECD countries since 1970. Furthermore, we find evidence that both R&D *and* human capital appear statistically and economically important in this catch up process as well as stimulating innovation directly. Trade, by contrast, plays a more modest role in productivity growth.

JEL CLASSIFICATION: O0, O3, O4

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

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Mapping the Two Faces of R&D: Productivity Growth in a Panel of OECD Industries

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1. Introduction

This paper provides an empirical investigation of the idea 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 perhaps received most attention in the existing empirical literature. The second role is in facilitating the understanding and imitation of others' discoveries. Some knowledge is 'tacit', difficult to codify in manuals and textbooks, and hard to acquire without direct investigation.[1] By actively engaging in R&D in a particular intellectual or technological field, one acquires such tacit knowledge and can more easily understand and assimilate the discoveries of others. Even then, the transfer of technology may be far from automatic. Take the example of 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.[2] In other words, R&D is as crucial for technology transfer as for innovation, and plays a role in developing 'absorptive capacity'.

We investigate these ideas within an empirical framework in which innovation and technology transfer provide two sources of productivity growth for a country behind the technological frontier. We use a country's distance from the technological

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[1] For further discussion of the role and importance of tacit knowledge, see David (1992) and Rosenberg (1982).

[2] An example cited by Arrow (1969).

frontier in a particular industry as a direct measure of the potential for technology transfer, where the frontier is defined 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 (through innovation), and whether R&D's effect on TFP growth depends upon a country's level of TFP relative to the frontier (the further a country lies behind the technological frontier, the greater the potential for R&D to increase TFP growth through technology transfer). Relative TFP is measured using a superlative index number approach, and the paper relates to the literatures concerned productivity measurement and convergence across countries and industries. The idea that productivity levels may vary across countries, and that these variations provide the opportunity for less advanced countries to benefit from technology transfer has a long history in both the economic and economic history literatures. Traditionally, much of the analysis has been undertaken at the whole-economy level.[3] More recently, a number of studies have documented levels of TFP across countries and investigated productivity convergence at the industry-level: two key findings are that substantial TFP differences exist and that the extent of these differences varies across individual industries.[4]

A somewhat independent literature has examined the determinants of industry-level productivity growth within individual economies. In particular, a large number of studies have focused on the role of research and development (R&D) activities in explaining rates of TFP growth.[5] A central assumption of this literature is that

[3]See, for example, Abramovitz (1986), Benhabib and Spiegel (1994), Gerschenkron (1962), Nelson and Phelps (1966), and Parente and Prescott (1994).

[4]These results cast doubt on the assumption of neutral technology differences (where technologies differ only by a country-specific constant) employed by many trade economists. Representative examples of the literature on cross-country levels of TFP include Acemoglu and Zillibotti (1998), van Ark and Pilat (1993), Bernard and Jones (1996a,b), Dollar and Wolff (1994), Dowrick (1989), Jorgenson and Kuroda (1990), Hansson and Henrekson (1994), Harrigan (1997, 1998), O'Mahony (1998), Pilat (1996), Prescott (1998), and Hall and Jones (1998).

[5]Classic references in this literature include Griliches (1980) Griliches and Lichtenberg (1984),

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R&D drives economic growth through the stream of innovations that it generates. More recently, an emerging empirical literature has considered the role of international R&D knowledge spillovers in explaining productivity growth. Some of these papers have left the precise mechanism unspecified (e.g. Bernstein and Mohnen, 1998), others have sought a "paper trail" through use of patent technology class (e.g. Branstetter, 1996), patent applications (Eaton and Kortum, 1996), patent citations (Jaffe and Trajtenberg, 1998), Foreign Direct Investment (Lichtenberg and Von Pottelsberghe de la Potterie (1996)), or trade flows (Keller, 1997, 1999; Coe and Helpman, 1995).[6]

This paper also examines the role of technology transfer in explaining productivity growth at the industry level. However, in contrast to the empirical literature on international R&D knowledge spillovers, we employ relative TFP levels as a direct measure of distance from the technological frontier in a particular industry.[7] We also allow a country's *own* R&D activity in a particular industry to play a central role in the process of technology transfer. Since we employ a direct measure of distance from the technological frontier, the analysis allows for spillovers of knowledge from both formal R&D investments and informal sources of productivity growth (e.g. learning by doing).[8] This is not to say that, in equilibrium, all knowledge will diffuse from the technological frontier: we control for a variety of observed (e.g. R&D activity) and unobserved country-industry characteristics that affect the ease of technology transfer. The role of own R&D activity in developing absorptive capacity is an idea that has received little attention in the literature on international R&D knowledge spillovers.

and Mansfield (1980). A recent survey is contained in Mohnen (1996).

[6]Other studies that have employed R&D or patent data to analyse international knowledge spillovers include Bayoumi *et al.* (1996), Coe, Helpman and Hoffmaister (1997), and Eaton and Kortum (1999).

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

[8]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).

In terms of that literature, the second 'face' of R&D is concerned with the interaction between domestic and foreign R&D activity.

In the cross-country growth literature, there has been considerable recent interest in the roles of human capital[9] and international trade[10] in the process of economic growth. We examine the role of these factors in explaining productivity growth at the industry-level, and carefully evaluate the robustness of our results concerning the two faces of R&D activity to the inclusion of these covariates. The empirical framework is extended to allow both human capital and international trade to affect rates of innovation *and* technology transfer. We implement our model on a panel dataset of 13 manufacturing industries in 12 OECD countries over the period 1970-92. Across a wide range of different econometric specifications, we find a positive and statistically significant effect of R&D on both rates of innovation and rates of technology transfer. This result is robust to a number of different adjustments in the measurement of TFP (e.g. controlling for cross-country differences in hours worked and country-industry specific mark-ups of price over marginal cost), and to the inclusion of information on human capital and international trade. R&D does indeed have two faces. Consequently, we argue that the social rate of return for R&D has been generally underestimated, in so far as most studies have focused on the US, which is typically the technological leader in our data. Increases in educational attainment are found to raise TFP growth through both innovation and technology transfer, while increased trade with the frontier country has a (weakly) positive effect on TFP growth through the speed of technology transfer but does not affect rates of innovation.

The structure is as follows. Section 2 introduces the theoretical framework. Section 3 discusses the econometric specification. Section 4 introduces the data and undertakes

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[9]See, *inter alia*, Barro and Lee (1994), Benhabib and Spiegel (1994) and Krueger and Lindahl (1998).

[10]See, for example, Edwards (1998), Frankel and Romer (1999), and Harrison (1996).

some data description. Section 5 presents the econometric results. Section 6 evaluates the quantitative importance of R&D and human capital in explaining both rates of productivity growth and changes in estimated steady-state relative TFP. Section 7 summarizes our conclusions.

2. Theoretical Framework

Denote countries by $i = 1, ..., N$ and manufacturing industries by $j = 1, ..., J$. Value added (Y) in each manufacturing sector at time t is produced with labour (L) and physical capital (K) according to a standard neoclassical production technology (2.1),

$$Y_{ijt} = A_{ijt}.F_j(L_{ijt,}K_{ijt})$$ (2.1)

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. We allow TFP (A) to vary across countries i, sectors j and time t; we term the economy with the highest level of TFP in sector j at time t the frontier $(i = F)$.

Following the existing literature on R&D and TFP growth (see for example Griliches and Lichtenberg (1984)),[11] we assume that TFP is a function of the stock of R&D knowledge (G_{ijt}) and a residual set of influences (B_{ijt}),

$$A_{ijt} = \Psi(B_{ijt}, G_{ijt}).$$ (2.2)

Taking logarithms in (2.2) and differentiating with respect to time, we obtain,

$$\frac{\dot{A}_{ijt}}{A_{ijt}} = \nu_{ijt}.\frac{\dot{B}_{ijt}}{B_{ijt}} + \eta_{ijt}.\frac{\dot{G}_{ijt}}{G_{ijt}}$$ (2.3)

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[11]The substantive assumption here is separability between R&D and other factors of production. The alternative approach embracing non-separability, followed by authors such as Bernstein and Nadiri (1989) and Nadiri and Kim (1996), requires estimating the (industry specific) user cost of R&D.

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where $\eta \equiv (dY/dG).(G/Y)$ is the elasticity of output with respect to the R&D knowledge stock (G) and $\nu \equiv (dY/dB).(B/Y)$ is the elasticity of output with respect to the residual set of influences (B). Denote real R&D expenditure by R and the rate of depreciation of the R&D knowledge stock by φ. Note that $\dot{G} = R - \varphi.G$, and, if we assume φ is small,[12] equation (2.3) may be rewritten in terms of the ratio of R&D expenditure to output,

$$\frac{\dot{A}_{ijt}}{A_{ijt}} = \nu_{ijt}.\frac{\dot{B}_{ijt}}{B_{ijt}} + \rho_{ijt}.\frac{R_{ijt}}{Y_{ijt}} \tag{2.4}$$

where $\rho = dY/dG$ is the rate of return or marginal product of R&D. Moving to discrete time, equation (2.4) becomes,

$$\Delta \ln A_{ijt} = \nu_{ijt}.\Delta \ln B_{ijt} + \rho_{ijt}.\frac{R_{ijt-1}}{Y_{ijt-1}}. \tag{2.5}$$

R&D activity is modelled as having a direct effect on TFP growth. The theoretical rationale for this effect is provided by models of endogenous innovation and growth.[13] These models emphasise the non-rivalry and partial excludability of knowledge - new ideas can be used at zero marginal cost in the research sector, while each innovator can appropriate the returns from their discovery as a result of patent protection. R&D affects rates of TFP growth because it results in innovations, and the expected flow of profits from acquiring the patent to a new technology provides the economic incentive to engage in R&D. Appendix C presents a simplified general equilibrium model of endogenous innovation and growth, based on Aghion and Howitt (1992), in which each innovation augments the quality or productivity of existing goods. An equation for TFP growth is derived, directly analogous to (2.5), in which R&D activity has a direct effect on TFP growth. We then extend the conventional model to allow for

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[12] If we explicitly assume an R&D depreciation rate then (2.3) can be estimated directly. We adopt this strategy as a robustness test below, but note the great uncertainty surrounding what actually is the appropriate rate of depreciation for knowledge.

[13] See for example Aghion and Howitt (1992) and Romer (1990).

the possibility of technology transfer from frontier to non-frontier countries within the same industries.[14] This implies that TFP growth in the frontier country induces faster TFP growth in follower countries by expanding the production possibility set. Furthermore, the speed of international diffusion of technology will depend upon both relative levels of TFP with the frontier and industry specific characteristics. This suggests,

$$\triangle \ln B_{ijt} = \pi_{ijt}.\triangle \ln A_{Fjt} - \sigma_{ijt}.\ln \left(\frac{A_i}{A_F} \right)_{jt-1} + u_{ijt} \qquad (2.6)$$

where $\ln (A_i/A_F)_{jt}$ denotes the relative level of TFP and u_{ijt} captures all other stochastic influences on TFP growth (see next section for further discussion). Since TFP in a non-frontier country lies below the level in the frontier, $\ln (A_i/A_F)_{jt}$ is negative. The smaller $\ln (A_i/A_F)_{jt}$, the further country i lies behind the technological frontier and the greater the potential for technology transfer. Hence, technology transfer implies a negative estimated coefficient on $\ln (A_i/A_F)_{jt}$ in equation (2.6). Substituting into (2.5) yields

$$\triangle \ln A_{ijt} = \beta_{ijt}.\triangle \ln A_{Fjt} - \delta_{ijt} \ln \left(\frac{A_i}{A_F} \right)_{jt-1} + \rho_{ijt}. \left(\frac{R}{Y} \right)_{ijt-1} + u_{ijt} \qquad (2.7)$$

where β_{ijt} captures the instantaneous effect of changes in frontier growth on growth in non-frontier countries and δ_{ijt} measures the rate of technology transfer.

Much of the existing theoretical literature on R&D and productivity growth emphasizes the links between R&D and innovation. However, a small number of theoretical papers[15] have argued that R&D may play an important role in enabling agents to imitate or adopt existing technologies. Cohen and Levinthal (1989) capture this idea by speaking of the 'two faces of R&D: innovation and learning.' Only by doing active research in an area does one learn about the current state-of-the-art technologies and

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[14]See also Nelson and Phelps (1966), Benhabib and Spiegel (1994), and Bernard and Jones (1996a,b).

[15]See in particular Cohen and Levinthal (1989) and Neary and Leahy (1999).

become able to imitate those technologies. As a result, technology transfer depends upon the technical competence and skills of agents in the adopting country or industry, and this has led to the use of the term 'absorptive capacity' in the literature.[16] Closely related is the idea that some elements of knowledge are not easily codified and are instead 'tacit', where this second term is typically used to refer to information only gained by familiarity with and active participation in an intellectual or technical field. A wide range of case study evidence has been put forward to support the role of 'tacit knowledge' in the history of technology and in economic development.[17] However, there has been very little econometric analysis of the idea that R&D may have a second role or 'face' in terms of the imitation of existing technologies.

Appendix C extends the theoretical model of endogenous innovation and growth referred to above to incorporate a role for R&D activity in technology transfer.[18] A simple specification allows the size of the quality improvement wrought by an innovation to be a function of the gap with the frontier economy in that industry. An equation for TFP growth is derived that implies that R&D activity enters equation (2.7) both linearly and as an interaction term with the size of the TFP gap. We capture this idea by generalizing the specification in equation (2.7) to allow the rate of technology transfer in non-frontier economies to be a function of R&D activity,[19] i.e.

$$\delta_{ijt} = \delta_1 + \delta_2 \left(\frac{R}{Y} \right)_{ijt-1}.$$

(2.8)

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[16]See for example the informal discussion in Romer (1993) and Rosenberg (1982, Chapter 11).

[17]See for example Rosenberg (1982, chapter 11) and the discussion in David (1992).

[18]For alternative theoretical models in which R&D may have both an innovative and imitative role, see Cohen and Levinthal (1989), Grossman and Helpman (1991), Neary and Leahy (1999), and Segerstrom (1991).

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

Substituting (2.8) into (2.7) generates our preferred model

$$
\begin{aligned}
\triangle \ln A_{ijt} = {} & \beta \triangle \ln A_{Fjt} - \delta_1 \ln \left(\tfrac{A_i}{A_F} \right)_{jt-1} - \delta_2 . \left(\tfrac{R}{Y} \right)_{ijt-1} . \ln \left(\tfrac{A_i}{A_F} \right)_{jt-1} \\
& + \rho \left(\tfrac{R}{Y} \right)_{ijt-1} + u_{ijt}
\end{aligned}
\tag{2.9}
$$

Notice that we have imposed a common coefficient on TFP growth in the frontier (β) and the linear R&D intensity variable (ρ) relative to equation (2.7). In fact, the return to an additional unit of R&D intensity will depend on how far an industry is behind the leading country $\left(\rho - \delta_2 . \ln \left(\tfrac{A_i}{A_F} \right)_{jt-1} \right)$. Our theory predicts that the social return to R&D is greater for non-frontier countries who have lower relative levels of TFP (that is, for whom $ln \left(\tfrac{A_i}{A_F} \right)$ is more negative). This is the particular structure we put on the heterogeneous returns to R&D in our dataset. In Section 5.3 we address the adequacy of this approach compared to a more general technique (e.g. Pesaran and Smith, 1995) of allowing the coefficients on R&D and the other covariates to take on different values for every individual industry-country pair (e.g. we estimate 113 individual ρ_{ij}).

In this paper we are particularly interested in investigating the extent to which R&D facilitates the international transfer of technology within an industry. Of course technology can also be transferred across industries and this conduit of transfer has been investigated more extensively in the literature (see Griliches, 1992, for a survey). The basic problem in this literature is constructing the appropriate "knowledge flow matrix", which specifies *ex ante* who gains knowledge from whom.[20] In the empirical application below our main interest is in examining international spillovers at the industry level, an area where there has been less empirical work. Since our main aim is to obtain robust estimates of the coefficients in (2.9) we also conduct many

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[20]Different possibilities include input-output matrices, mappings between the users and suppliers of innovations, technology classes from patent statistics or patent citation information. Jaffe (1986) is perhaps the most convincing attempt, but this is highly data intensive.

specification tests including the addition of a term that captures the amount of R&D done in all other industries within the same country, $\sum_{k \neq j} \left(\frac{R}{Y}\right)_{ikt}$. 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). Given the lack of consensus for the appropriate matrix, we leave a more sophisticated treatment of inter-industry spillovers for future work.

Our baseline equation (2.7) assumes that R&D is the critical factor in generating innovation and catch up. Many authors have emphasised human capital and trade as alternative sources of growth. In the empirical section we extend the model in a natural way by adding these two factors as sources of growth to (2.9) to obtain

$$\triangle \ln A_{ijt} = \beta \triangle \ln A_{Fjt} - \delta_1 \ln \left(\frac{A_i}{A_F}\right)_{jt-1} - \delta_2 . \left(\frac{R}{Y}\right)_{ijt-1} . \ln \left(\frac{A_i}{A_F}\right)_{jt-1}$$

$$-\delta_3 . H_{i,t-1} . \ln \left(\frac{A_i}{A_F}\right)_{jt-1} - \delta_4 . \left(\frac{IMPS}{Y}\right)_{ijt-1} . \ln \left(\frac{A_i}{A_F}\right)_{jt-1} \qquad (2.10)$$

$$+\rho_1 \left(\frac{R}{Y}\right)_{ijt-1} + \rho_2 H_{it-1} + \rho_3 \left(\frac{IMPS}{Y}\right)_{ijt-1} + u_{ijt}$$

where H is a measure of levels of human capital and $\left(\frac{IMPS}{Y}\right)$ is a measure of trade intensity (see data section below for details of how these are measured).

3. Econometric Specification

Notice that (2.9), and its generalization (2.10), can also be considered as an equilibrium correction mechanism (ECM) (see Hendry, 1996). This representation has many attractive statistical properties. Consider an ADL(1,1) model where own TFP is cointegrated with frontier TFP,

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

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

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

This is equation (2.9), where the model is augmented with a term for the R&D intensity, $\alpha_2 = \beta$, and the coefficient on relative TFP $(1 - \alpha_1)$ is allowed to be a function of R&D intensity. It is clear from the above that the coefficient on the TFP gap term will measure the speed of convergence to the long-run steady state level of TFP.

There will clearly be unobserved country-industry characteristics, which affect rates of TFP growth and are not captured by our model. In terms of the theoretical model, these correspond to an unobserved component of $\triangle \ln B_{ijt}$ in equation (2.6). Moreover, it is likely that these unobserved country-industry characteristics will be correlated with the explanatory variables in (2.9). 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 allow for unobserved heterogeneity that is correlated with the explanatory variables by including a full set of fixed effects (ψ_{ij}) in the error term u_{ijt} in (2.6). Furthermore, there are world macroeconomic shocks which may raise TFP in all countries - a full set of time dummies is therefore included to control for these (T_t). All other factors are consigned to a serially uncorrelated error term (ε_{ijt}),

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

We thus obtain our final econometric specification of TFP growth in sector j of a non-frontier economy,

$$\triangle \ln A_{ijt} = \beta \triangle \ln A_{Fjt} - \delta_1 . \ln \left(\frac{A_i}{A_F} \right)_{jt-1} - \delta_2 \left[\left(\frac{R_i}{Y_i} \right) . \ln \left(\frac{A_i}{A_F} \right) \right]_{jt-1}$$
$$+ \rho \left(\frac{R}{Y} \right)_{ijt-1} + \psi_{ij} + T_t + \varepsilon_{ijt}. \tag{3.1}$$

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In contrast to all other economies, there is no potential for technology transfer in the frontier. TFP growth in sector j in the frontier is modelled as in the conventional specification,

$$\Delta \ln A_{Fjt} = \psi_{Fj} + \rho . \left(\frac{R}{Y}\right)_{Fjt-1} + T_t + \varepsilon_{Fjt}. \qquad (3.2)$$

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. Our baseline results estimate equations (3.1) and (3.2) 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 $E\left(\varepsilon_{ijt}\middle| \left(\frac{R}{Y}\right)_{ijt-1}\right) = 0$ and $E\left(\varepsilon_{ijt}\middle| \ln\left(\frac{A_i}{A_F}\right)_{jt-1}\right) = 0$; where $E(.|.)$ is the conditional expectations operator. 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. A second problem is that the weak exogeneity assumption is less plausible for productivity growth in the frontier ($\Delta \ln A_{Fjt}$) in equation (3.1); there may be common shocks in an industry that are not controlled for by the other covariates. The structure of our model implies that past R&D in the frontier is a natural instrument for frontier growth, as it should not have a direct effect on TFP in non-frontier industries unless it successfully generates innovation. In the results section we compare our baseline OLS results with IV estimates. Finally, there may be finite sample biases with the

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within group estimator even if the regressors are all pre-determined. The results in Nickell (1981), however, find 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.

It is useful to consider the long-run determinants of the level of TFP. Having specified the growth process in frontier and non-frontier economies, we can combine equations (3.1) and (3.2) to obtain a dynamic equation for the level of TFP in country i relative to the frontier in sector j,

$$
\begin{aligned}
\triangle \ln \left(\frac{A_i}{A_F} \right)_{jt} = (\psi_{ij} - \psi_{Fj}) + \rho \left(\left(\frac{R}{Y} \right)_{ijt-1} - \left(\frac{R}{Y} \right)_{Fjt-1} \right) + \beta \triangle \ln A_{Fjt} \\
- \left(\delta_1 + \delta_2 . \left(\frac{R}{Y} \right)_{ijt-1} \right) . \ln \left(\frac{A_i}{A_F} \right)_{jt-1} + \chi_{ijt}
\end{aligned}
\tag{3.3}
$$

where $\chi_{ijt} = \varepsilon_{ijt} - \varepsilon_{Fjt}$. We consider a steady-state equilibrium, in which the independent variables in equations (3.1) and (3.3) are constant over time (e.g. $\left(\frac{R}{Y} \right)_{Fjt} = \left(\frac{R}{Y} \right)_{Fjt-1}$ and $\left(\frac{R}{Y} \right)_{ijt} = \left(\frac{R}{Y} \right)_{ijt-1}$ for all i and j), and in which TFP in a sector j of all countries i grows at the same constant rate ($\triangle \ln A_{ij} = \triangle \ln A_{Fj}$ and $\triangle \ln(A_i/A_F)_j = 0$ for all i). This common rate of TFP growth equals steady-state TFP growth in the frontier, which is determined according to equation (3.2). Thus, setting the left-hand-side of (3.3) equal to zero and substituting for $\triangle \ln A_{Fjt}$, we may solve for steady-state TFP in country i relative to the frontier in sector j,

$$
\ln \left(\frac{A_i}{A_F} \right)_{jt}^* = \frac{\psi_{ij} + \rho . \left(\frac{R}{Y} \right)_{ijt} - (1 - \beta) . \left(\psi_{Fj} + \rho . \left(\frac{R}{Y} \right)_{Fjt} \right) + \beta . T_t}{\left(\delta_1 + \delta_2 . \left(\frac{R}{Y} \right)_{ijt} \right)}
\tag{3.4}
$$

At the steady-state level of relative TFP in country i, TFP growth from innovation and technology transfer in country i exactly equals TFP growth from innovation in the frontier. Equation (3.4) has an intuitive interpretation. The level of TFP in country i is closer to that in the frontier, the higher is own R&D, the larger the country-industry fixed effect (ψ_{ij}), and the greater the speed at which technology transfer occurs (either

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autonomously (δ_1) or through R&D-based learning (δ_2)).[21] Taking as given the speed of technology transfer (δ_1 and δ_2) and the level of R&D in country i, an increase in frontier R&D results in a decrease in steady-state relative TFP in country i. This captures the fact that, as the rate of TFP growth in the frontier increases, steady-state TFP in country i must lie further behind the technological frontier in order for TFP growth through innovation and technology transfer to equal that through innovation in the frontier. However, if we differentiate with respect to frontier R&D in equation (3.1), and use the expressions for steady-state TFP growth in the frontier (3.2) and steady-state levels of relative TFP (3.4), it is clear that an increase in frontier R&D raises country i's steady-state rate of TFP growth and hence country i's absolute level of TFP. In exactly the same way that equation (2.9) may be extended to incorporate a role for levels of human capital and flows of international trade, so may equation (3.4) - as will be discussed further below.

This concludes the econometric section, we now move on to a discussion of the empirical measurement of TFP and a preliminary data analysis.

4. Data Description

4.1. Data sources and sample size

The data used in the empirical application comes from a number of sources (see Appendix A for details). 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 is all R&D performed

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[21]Notice that the numerator of (3.4) is negative and the denominator positive, ($\ln (A_i/A_F)$ is less than zero for a non-frontier country).

by the business sector (from all sources of finance, including government subsidies). 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 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 1: sample size for TFP data by industry and country, 1970-1992

ISIC	Can	Dnk	Fin	Fra	Ger	Ita	Jap	Net	Nor	Swe	UK	US	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.

4.2. TFP growth and relative levels across countries and industries

The theoretical model of Section 2 implies a relationship between TFP growth, TFP relative to the frontier, and the economic variables that potentially influence innovation and technology transfer. This section analyses rates of TFP growth and the evolution of relative levels of TFP across countries and industries.

The analysis here relates to several recent studies of comparative TFP levels. For example, Bernard and Jones (1996a,b) analyse convergence across industries and countries at the more highly aggregated level of the manufacturing sector as a whole and non-manufacturing industries. Both papers evaluate the extent to which convergence has occurred in OECD countries and industries, whereas the concern of this paper is to estimate an econometric model of the determinants of productivity growth (within which technology transfer will have a role to play). Harrigan (1997) provides mea-

sures of relative TFP levels at a similar level of disaggregation to that employed in this paper. However, these are used to explain patterns of international specialization across manufacturing industries rather than rates of productivity growth. Harrigan (1998) evaluates cross-country differences in TFP for 10 OECD countries in 5 machinery sectors from 1980-89, but does not consider the roles of R&D, human capital, and international trade in determining rates of TFP growth.

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 function,[22]

$$\triangle TFP_{ijt} = \ln\left(\frac{Y_{ijt}}{Y_{ijt-1}}\right) - \frac{1}{2}(\alpha_{ijt} + \alpha_{ijt-1})\ln\left(\frac{L_{ijt}}{L_{ijt-1}}\right)$$
$$- \left(1 - \frac{1}{2}(\alpha_{ijt} + \alpha_{ijt-1})\right)\ln\left(\frac{K_{ijt}}{K_{ijt-1}}\right) \tag{4.1}$$

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 gross fixed capital formation (converted to US dollars using a capital PPP).

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[22]See Caves et al. (1982b). One of the classic references on measuring TFP growth is Solow (1957).

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,[23]

$$\alpha_{ijt} = \xi_{ij} + \phi_j . \ln\left(K_{ijt}/L_{ijt}\right). \tag{4.2}$$

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 (4.1) and below.

We measure the level of TFP in country relative to the frontier using an analogous superlative index number derived from the translog production function.[24] 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 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,

$$MTFP_{ijt} = \ln\left(\frac{Y_{ijt}}{\bar{Y}_{jt}}\right) - \tilde{\sigma}_{ijt}\ln\left(\frac{L_{ijt}}{\bar{L}_{jt}}\right) - (1 - \tilde{\sigma}_{ijt})\ln\left(\frac{K_{ijt}}{\bar{K}_{jt}}\right) \tag{4.3}$$

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

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[23]See Caves *et al.* (1982b) and Harrigan (1997).
[24]See also Denny and Fuss (1983a) and (1983b).

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 (4.2) 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 $\ln \left(\frac{A_i}{A_F} \right)_{jt}$ in section 2),[25]

$$RTFP_{ijt} = MTFP_{ijt} - MTFP_{Fjt}. \tag{4.4}$$

Before beginning the formal analysis of the results, we first examine some simple descriptive statistics. As mentioned above, we make several adjustments to our basic measures of TFP as suggested by the literature. 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 2 the mean annual growth rates of our preferred measure are given by industry. It can be seen that there is considerable heterogeneity in rates of TFP growth across both countries and manufacturing industries.

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[25]Note that equation (4.3) 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.

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

ISIC	Can	Dnk	Fin	Fra	Ger	Ita	Jap	Net	Nor	Swe	UK	US
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.

To illustrate our method, Figure 1 plots relative TFP (RTFP) for one industry - Paper, Printing and Publishing (ISIC 34). The US 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 US. Japan is notable for starting off as one of the countries furthest from the US 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 US, and Britain did not start catching up until the 1980s. The picture varies by industry, but Table 3 shows which country has the highest (the frontier) and second highest level of relative TFP in 1971, 1981, and 1991.

Table 3: relative TFP and the identity of frontier country, 1971, 1981, and 1991 (skills adjustment and hours)

ISIC		1971	1981	1990			1971	1981	1990
31	First	Jap	Jap	US	381	First	US	Ger	Ger
	Second	Can	US	Ita		Second	Ger	US	US
	Mean	0.65	0.69	0.77		Mean	0.78	0.85	0.88
	S.D.	0.20	0.18	0.17		S.D.	0.32	0.17	0.10
32	First	Fra	Dnk	Nld	382	First	Ger	Ger	US
	Second	Swe	Fra	Fra		Second	US	Ita	Fra
	Mean	0.72	0.77	0.78		Mean	0.88	0.90	0.93
	S.D.	0.18	0.17	0.19		S.D.	0.10	0.07	0.05
33	First	US	US	US	383	First	US	US	US
	Second	Ger	Ger	Swe		Second	Fra	Fra	Fra
	Mean	0.79	0.85	0.81		Mean	0.75	0.88	0.94
	S.D.	0.17	0.15	0.12		S.D.	0.31	0.15	0.06
34	First	US	US	Nld	384	First	US	US	US
	Second	Fra	Fra	US		Second	Ger	Ger	Ger
	Mean	0.62	0.68	0.80		Mean	0.71	0.88	0.95
	S.D.	0.20	0.18	0.15		S.D.	0.19	0.15	0.04
35	First	Jap	Ger	Ger	385	First	US	Fra	Fra
	Second	Ger	Jap	Jap		Second	Ger	US	US
	Mean	0.55	0.70	0.79		Mean	0.67	0.82	0.87
	S.D.	0.23	0.20	0.19		S.D.	0.33	0.21	0.09
36	First	Can	Can	Nld	39	First	US	Dnk	US
	Second	Ger	Fra	Fra		Second	Dnk	US	Ger
	Mean	0.78	0.85	0.86		Mean	0.77	0.71	0.68
	S.D.	0.14	0.11	0.12		S.D.	0.24	0.24	0.22
37	First	US	Jap	Jap	30	First	US	US	Nld
	Second	UK	US	Ita	(Total)	Second	Can	Nld	US
	Mean	0.55	0.66	0.72		Mean	0.68	0.79	0.81
	S.D.	0.23	0.23	0.14		S.D.	0.15	0.14	0.13
38	First	US	US	Nld					
	Second	Ger	Ger	US					
	Mean	0.54	0.71	0.76					
	S.D.	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. are the mean and standard deviation of RTFP across countries. A value of mean closer to unity corresponds to a higher average level of relative TFP.

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 we see examples of loss of technological leadership as one economy 'leapfrogs' another (e.g. ISIC 35 and 381).[26] The econometric model suggests that it is not the identity of the frontier economy *per se* that is important, but rather the measure of distance from the technological frontier, which we use to capture the potential for technology transfer.[27]

Table 3 also reports the sample mean and standard deviation of relative TFP (as measured by (4.4)) across countries for each industry in the years 1971, 1981, and 1991. 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 1991 than 1971, and, in all industries except two (ISIC 32 and 36), the standard deviation is lower in 1991 than in 1971. This suggests convergence of levels of relative TFP within OECD manufacturing industries during the sample period. This conclusion is confirmed in Figures 2 and 3, which respectively graph relative TFP (not exponentiated) and the standard deviation of relative TFP (again not exponentiated). The lines marked with a circle in Figure 2 indicate the US and those marked with a plus indicate Japan. In seven of the nine two-digit industries there is a marked downward trend in the standard deviation over time (evidence of

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

[27]If relative levels of TFP are measured with error, then so will be the identity of the frontier in individual industries and time periods. If our measure of distance from the technological frontier is subject to classical measurement error, the parameters of interest will be attenuated towards zero. In the econometric analysis that follows, we are careful to consider the robustness of our estimates to alternative measures of relative TFP.

σ-convergence in the terminology of the cross-country growth literature).[28]

At first sight, this contrasts with the results of Bernard and Jones (1996a,b), who find that the majority of the *convergence* in economy-wide productivity amongst OECD countries during 1970-87 is driven by non-manufacturing industries. In fact, the analysis in Bernard and Jones (1996a,b) is largely concerned with aggregate manufacturing and non-manufacturing sectors, and is therefore perfectly consistent with convergence in some manufacturing industries (see for example Bernard and Jones, 1994). There are two further important differences in what we do. First, we employ data on the skill composition of the workforce to control for differences in labour quality across countries and over time. Second, rather than assuming a Cobb-Douglas productivity technology, we measure relative TFP using a superlative index number approach. The second of these differences on its own is quantitatively important. If we recalculate relative TFP using data on hours and the skill composition of the workforce, but assume a Cobb-Douglas production technology with labour's exponent equal to the time-averaged share of labour compensation in value-added (for 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. Thus, measuring relative TFP with a superlative index number derived from the translog production function strengthens the finding of productivity convergence within OECD manufacturing industries.

One of the striking features of Table 3 is the continued strength of the US across a broad number of industries. Despite the international diffusion of technologies the US has managed to keep a lead, in part, we hypothesize due to its strong R&D performance in many industries. Table 4 tabulates average R&D intensities by industry. It is clear that the leaders in TFP also tend to have high R&D intensities. To what extent this

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[28]See, for example, Barro and Sala-i-Martin (1995).

relationship is robust to further econometric controls is the subject of the next section.

Table 4: average R&D intensity, 1974-1992

ISIC	Can	Dnk	Fin	Fra	Ger	Ita	Jap	Net	Nor	Swe	UK	US
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.

5. Empirical Results

5.1. TFP growth and technology transfer

We begin in Table 5 by showing estimates of the coefficients of a TFP growth equation with no R&D effects. In column (1) estimates are presented without controlling for fixed effects. 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. In column (2) we control for unobserved heterogeneity by using the within groups estimator. This increases (in absolute terms) the size of the gap term by a factor of three.[29] Column (3)

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[29]These results are robust to dropping any single industry or country.

re-estimates the basic specification instrumenting the gap term (with $RTFP_{ijt-2}$).[30] Treating this term as endogenous has no significant effect on the size of the coefficient. Column (4) uses only the data on total manufacturing (ISIC 30). Aggregation produces some upwards bias on the frontier growth variable, but, as before, we find that TFP growth in the frontier has a positive and statistically significant effect on rates of TFP growth in non-frontier countries. The coefficient on relative TFP is again negative and statistically significant at conventional levels.

In columns (5) to (9) we adjust our TFP measure to take account of differences in skill levels, hours worked, mark-ups, capacity utilization and industry specific PPPs respectively, as described in Appendix A. The basic TFP growth model is remarkably robust to all of these adjustments. While the identity of the frontier country shifts with these adjustments (e.g. the US is frontier less often when we take into account the longer hours worked), countries do not change rankings very dramatically. Moreover, what matters for the regressions is not the identity of the frontier, but the magnitude of relative TFP levels. We use TFP in the frontier as a measure of where the technological frontier lies in an industry and of how far each country lags behind the frontier. The econometric results are robust to using alternative measures of the technological frontier, such as a convex combination of TFP in the frontier and the second highest country, suggesting that the level of TFP in the leading country provides a good measure of where the technological frontier lies.[31]

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[30]This is valid in the absence of serial correlation. The Arellano and Bond (1991) LM statistic at the base of the table confirms that there is no evidence of serial correlation in this column. The specifications that do not control for fixed effects (column (1)) or are performed on aggregate data (column (4)) do show signs of serial correlation.

[31]For example, we replaced the definition of the frontier with the average of the relative TFPs of the leader and second follower and reestimated column (6). The estimated coefficent on relative TFP was -0.100 (standard error, 0.016) - very similar to that reported in Table 5.

Table 5: TFP growth equation

ΔTFP_{ijt}	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Obs	2033	2033	2033	203	1822	1822	1822	1822	1822
Years	74-92	74-92	74-92	74-92	74-92	74-90	74-90	74-90	74-90
ΔTFP_{Fjt}	0.132	0.128	0.134	0.352	0.140	0.134	0.121	0.106	0.100
	0.026	*0.027*	*0.027*	*0.082*	*0.028*	*0.031*	*0.030*	*0.032*	*0.030*
$RTFP_{ijt-1}$	-0.027	-0.081	-0.095	-0.135	-0.094	-0.092	-0.079	-0.078	-0.076
	0.005	*0.013*	*0.016*	*0.035*	*0.014*	*0.014*	*0.014*	*0.012*	*0.012*
Year dummies	yes	yes	yes		yes	yes	yes	yes	yes
Within groups		yes	yes	yes	yes	yes	yes	yes	yes
IV			yes						
Serial Correlation	2.336	0.649	0.230	1.680	0.783	0.430	0.030	0.232	0.111
p-value	*0.021*	*0.501*	*0.403*	*0.093*	*0.434*	*0.607*	*0.986*	*0.816*	*0.911*
Total Manufacturing				yes					
Adjustments to TFP									
Skills Adjustment					yes	yes	yes	yes	yes
Hours						yes	yes	yes	yes
Markup							yes	yes	yes
Capacity utilisation								yes	yes
PPP									yes

Notes: numbers in italics below coefficients are robust standard errors; observations are weighted with industry shares of a country's total manufacturing employment in 1970 as weights; instrument for $RTFP_{ijt-1}$ in column (3) is $RTFP_{ijt-2}$; serial correlation is a LM test (Arellano and Bond, 1991).

5.2. Mapping The Two Faces of R&D

We now investigate the role that R&D expenditure plays in productivity growth. 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, both 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.

In column (1) of Table 6, the basic TFP growth equation shown in Table 5 is repeated for reference. In column (2), we include the lagged level of R&D intensity, which enters positively and is statistically significant at the 5% level. In column (3), both the level and interaction between the R&D level and the productivity gap are included. 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 conventional levels. The linear term remains positive, but has lost precision and is no longer significant at conventional levels.

In columns (4) to (8), we adjust our TFP measure to take account of differences in skill levels, hours worked, mark-ups, capacity utilization and industry specific PPPs respectively. The way in which these adjustments are made is described in Appendix A. In column (4), we control for differences in skill levels. This correction alone yields a significant coefficient on the linear R&D intensity term, while the R&D interaction term remains significant at the 5% level. In column (5), we also control for differences in hours worked across countries. Both the R&D level and interaction terms remain statistically significant at the 5% level. In column (6), factor shares are adjusted for differential mark-ups across industries and countries. In column (7), capital is adjusted to account for differences in capacity utilization.. In column (8), we employ industry-specific output PPPs to convert value-added in each country into US dollars. The upshot of all of these corrections 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).

Table 6: impact of R&D on TFP growth equation

ΔTFP_{ijt}	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Obs	2033	2033	2033	1822	1822	1822	1822	1822
Years	74-92	74-92	74-92	74-92	74-90	74-90	74-90	74-90
ΔTFP_{Fjt}	0.128	0.121	0.121	0.132	0.122	0.111	0.091	0.084
	0.027	*0.026*	*0.026*	*0.027*	*0.030*	*0.029*	*0.032*	*0.030*
$RTFP_{ijt-1}$	-0.081	-0.084	-0.061	-0.078	-0.068	-0.056	-0.055	-0.060
	0.013	*0.013*	*0.014*	*0.015*	*0.016*	*0.016*	*0.014*	*0.014*
$(R/Y)_{ijt-1}$	-	0.411	0.207	0.397	0.418	0.446	0.306	0.290
		0.147	*0.170*	*0.187*	*0.179*	*0.178*	*0.153*	*0.172*
$(RTFP*(R/Y))_{ijt-1}$	-	-	-0.744	-0.653	-1.022	-1.106	-1.096	-0.882
			0.324	*0.331*	*0.344*	*0.339*	*0.329*	*0.257*
Year dummies	yes	yes	yes	yes	yes	yes	yes	yes
Within groups	yes	yes	yes	yes	yes	yes	yes	yes
Serial Correlation	0.649	0.479	0.514	0.564	0.635	0.177	0.272	0.026
p-value	*0.501*	*0.632*	*0.607*	*0.573*	*0.526*	*0.859*	*0.786*	*0.929*
Adjustments to TFP								
Skills Adjustment				yes	yes	yes	yes	yes
Hours					yes	yes	yes	yes
Markup						yes	yes	yes
Capacity Utilisation							yes	yes
PPPs								yes

Notes: numbers in italics below coefficients are robust standard errors; observations weighted with industry shares of a country's total manufacturing employment in 1970 as weights; serial correlation is a LM test (Arellano and Bond, 1991) distributed N(0,1) under the null.

All the results presented in Tables 5 and 6 refer to samples where we have pooled observations on frontier and non-frontier countries. The cross-equation restrictions implied by the theoretical model are imposed: that is, the coefficient on R&D (ρ) takes the same value in frontier and non-frontier economies.[32] Since $RTFP$ equals zero for the frontier, there is no $RTFP$ and no R&D interaction term in the equation

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[32] Also, of course, there is no term for frontier growth on the right hand side of the frontier growth equation ($\beta^F = 0$).

for TFP growth in the frontier. One concern is that the cross-equation restrictions may not be valid. Therefore, we also estimate the model for non-frontier countries only, dropping observations on countries that were the frontier in either the current or previous period. The results of this robustness test are presented in Tables B1 and B2 of Appendix B. The results are largely unchanged, and all the conclusions from the previous discussion apply to this smaller sample.

Our preferred measure of relative TFP is the one correcting for differences in hours worked and the skill composition of the workforce (column (5) of Table 6). Recall that our modelling strategy focuses on international intra-industry spillovers and does not consider domestic inter-industry knowledge spillovers. A full treatment of this is beyond the scope of the paper, but we have included economy-wide R&D intensity and its interaction as a specification test. Both variables took their expected signs but were insignificant at conventional levels. The industry-specific terms dominated over their more aggregate counterparts.[33]

Table B4 in Appendix B reports some further specification tests for our preferred measure of relative TFP. The first two columns experiment with using longer dynamics, while the third and fourth column employ the R&D knowledge stock rather than flow. These robustness checks confirm our main result that R&D has an impact on productivity growth, in particular through the interaction with RTFP.

5.3. R&D, trade, and human capital

The above analysis of the links between R&D and productivity growth has so far neglected the roles of international trade and human capital. One concern might be that R&D is proxying for these effects. In this section, we examine the robustness of our

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[33]For example, in the context of column (5) Table 6 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*).

earlier results to allowing each of these variables to affect innovation and technology transfer.

Nelson and Phelps (1966) and Benhabib and Spiegel (1994) emphasize that one positive externality of high levels of general human capital may be increased innovation and technology transfer.[34] Since this effect of human capital is thought to be an externality, we employ country-level data on the "percentage of higher school attained in the total population" from Barro and Lee (1994), denoted H_{it}.[35] Column (1) of Table 7 reproduces our earlier R&D results, using the measure of relative TFP that controls for differences in skills and hours worked. Column (2) introduces the level of the human capital variable, which is statistically significant at the 5% level. The coefficients on both R&D variables remain largely unchanged and statistically significant at conventional critical values. Column (3) extends the specification so that it includes a level and interaction human capital term. Both are statistically significant at the 5% level, suggesting an important role for human capital in innovation and technology transfer. The estimated coefficient on the interaction term is again negative: human capital has a greater positive effect on rates of TFP growth through technology transfer, the smaller a country's level of TFP relative to the frontier (the more negative $RFTP$). The conclusions concerning the effects of R&D are again unchanged.

The role of international trade is stressed in the literature using R&D or patent data to examine international knowledge spillovers.[36] Trade can effect productivity growth through a number of routes (e.g. technology spillover by the reverse engineering of imported goods, increased product market competition, or larger market size). There

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[34]See Bartel and Lichtenberg (1987) for microeconomic evidence on the complementarity between levels of human capital and the relative return to new technologies.

[35]See Appendix A for further details. Higher education is a more appropriate variable than secondary education for OECD countries. Gemmell (1996), for example, finds that only this education variable is significant in OECD growth equations.

[36]See, for example, Coe and Helpman (1995), Coe, Helpman and Hoffmaister (1997), and Keller (1997, 1999).

are many ways to introduce international trade into the model, and we take a simple approach here. The OECD bilateral trade database provides information for each industry in each country on the source of imports from trading partners in the OECD and on total imports from the rest of the world. Using these data, we construct three measures of import penetration for each industry in each country:

(i) imports from anywhere in the world,

(ii) imports from the frontier,

(iii) imports from non-OECD countries.

We begin by using the measure of imports from the frontier, scaled by output, denoted $\left(\frac{IMP}{Y}\right)_{ijt}$. In Column (4) of Table 7, we introduce the (lagged) level of the ratio of imports from the frontier to value-added into the R&D specification. The magnitude and statistical significance of the coefficients on the two R&D terms remain largely unchanged; the lagged import level term is itself positively signed and statistically significant at the 5% level. However, when we include an import interaction term as well in Column (5), the point estimate on the import level term falls by an order of magnitude and is no longer significant. The import interaction term has a negative sign and is statistically significant at the 5% level. Thus, trade with the frontier effects rates of productivity growth through technology transfer rather than through innovation. The positive effect of trade with the frontier on rates of productivity growth is greater the smaller a country's level of TFP relative to the frontier (the more negative $RTFP$).

Interestingly, the results with imports from anywhere in the 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.[37]

The most general model is presented in Column (6), where the R&D specification is augmented with level and interaction terms for both human capital and trade with the frontier. Both the R&D and human capital level terms are positively and statistically significant at the 5% level, while both the R&D interaction and human capital interaction terms are negatively signed and statistically significant at the 5% level. This suggests that both R&D activity and general levels of human capital have a positive effect on productivity growth through two distinct channels - innovation and technology transfer. Although the import interaction term is negatively signed and statistically significant at the 10% level, the coefficient on the import level term is small in magnitude and statistically insignificant. 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.

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[37]These results do 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).

Table 7: impact of R&D, trade, and human capital on TFP growth

ΔTFP_{ijt}		(1)	(2)	(3)	(4)	(5)	(6)
Obs		1822	1822	1822	1822	1822	1822
Years		74-90	74-90	74-90	74-90	74-90	74-90
ΔTFP_{Fjt}	β	0.122	0.121	0.119	0.122	0.119	0.117
		0.030	*0.030*	*0.030*	*0.030*	*0.030*	*0.030*
$RTFP_{ijt-1}$	δ_1	-0.068	-0.064	-0.023	-0.069	-0.070	-0.028
		0.016	*0.016*	*0.021*	*0.016*	*0.016*	*0.022*
$(R/Y)_{ijt-1}$	ρ_1	0.418	0.375	0.412	0.426	0.457	0.439
		0.179	*0.176*	*0.173*	*0.179*	*0.180*	*0.175*
$(RTFP * (R/Y))_{ijt-1}$	δ_2	-1.022	-1.110	-0.838	-1.002	-0.910	-0.770
		0.344	*0.347*	*0.348*	*0.345*	*0.348*	*0.350*
H_{it-1}	ρ_2	-	0.335	0.228	-	-	0.254
			0.130	*0.124*			*0.124*
$(RTFP * H)_{it-1}$	δ_3	-	-	-0.457	-	-	-0.422
				0.137			*0.139*
$(IMPS/Y)_{ijt-1}$	ρ_3	-	-	-	0.018	-0.003	0.001
					0.008	*0.013*	*0.011*
$(RTFP * (IMPS/Y))_{ijt-1}$	δ_3	-	-	-	-	-0.081	-0.064
						0.033	*0.034*
Serial Correlation (p-value)		*0.524*	*0.586*	*0.381*	*0.526*	*0.473*	*0.382*
Year dummies		yes	yes	yes	yes	yes	yes
Within groups		yes	yes	yes	yes	yes	yes
Skills Adjustment		yes	yes	yes	yes	yes	yes
Hours		yes	yes	yes	yes	yes	yes

Notes: numbers in italics below coefficients are robust standard errors. Observations are weighted using industry shares of total manufacturing employment; IMPS is imports from the frontier.

Many further experiments were conducted on the results. First, we were concerned that the coefficient on frontier TFP growth could be biased by the presence of correlated shocks in an industry across different countries in the world. The structure of the model suggests that the natural instruments for frontier TFP growth are lagged

values of R&D, human capital, and the frontier's imports from anywhere in the world. According to our model, these only have an indirect effect on TFP growth in other countries through stimulating innovation in the frontier industry itself (as measured by frontier TFP growth).[38] In fact, when we reestimated column (6) of Table 7 by instrumental variables, rather than fall the coefficient on frontier TFP growth rose to 0.411, although it had a large standard error (0.322). Although also measured with less precision, the coefficients on the other variables were largely unaffected.[39]

Secondly, the role of the aggregate human capital variable is open to different interpretations (see Krueger and Lindahl, 1998 for a critical discussion). To check the robustness of the 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.[40] This could be due to sample size, but it is suggestive of externalities through innovation rather than the standard augmented Solow model. We also examined whether it was country-wide imports or country-wide R&D which mattered for productivity rather than industry-specific measures. The data prefers our specification in Table 7.[41] We experimented with various other non-linearities in the variable of interest (for example, quadratic terms in lagged human capital). None of these experiments lead us to change our preferred specification.[42]

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[38]For a similar idea applied to US economic growth, see Raa and Wolff (1999).

[39]The results were as follows (standard errors in parantheses): $\Delta TFP_{ijt} = 0.236(0.132)H_{it-1} - 0.418(0.144)RTFP_{ijt-1} * H_{it-1} + 0.321(0.218)(R/Y)_{ijt-1} - 0.789(0.364)RTFP_{ijt-1} * (R/Y)_{ijt-1} +$ all other variables in column (6), Table 7.

[40]The specification in column (6) of Table 7 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.

[41]In the model of column (6) Table 7, the estimated coefficient (*standard error*) on the linear country-wide R&D intensity was 0.481 (*0.372*), and that on the interaction of country-wide R&D intensity with RTFP was 0.540 (*0.629*). The estimated coefficient (*standard error*) on the linear country-wide imports from the frontier term was -0.003 (*0.001*), and that on the interaction of country-wide imports from the frontier with RTFP was -0.005 (*0.003*).

[42]For example, the specification in column (6) of Table 7 was augmented with a term in the level

Finally, we consider the possibility of heterogeneity in the coefficients across industries and countries. Recall that all our models have 113 fixed effects included (one for each country-industry pair). Table 8 reports the results from specifications which allow the coefficients to also 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 8 estimates the specification in column (6) of Table 7 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 column (2) of Table 8, we report some results of these experiments[43]. The estimates in column (1) and (2) are quite 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 using within groups. This is precisely what would be expected from our theoretical model 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 this further, we split the sample by the median value of relative TFP into those countries that are far from the frontier ('large gap') and those that are closer to the frontier ('small gap').[44] These results reveal that the effect of R&D and human capital are more important for those

of human capital squared and an interaction term between human capital squared and relative TFP. Neither term was significant at conventional levels of significance. The estimated coefficients (*standard errors*) on the level and interaction terms were -0.0008 (*0.004*) and 0.002 (*0.011*) respectively.

[43] 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.

[44] 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.

countries that are far from the technological frontier. In summary, we think that this corroborates our qualitative findings from the more parsimonious models of Table 7.

Table 8: 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 ($RTFP \succeq -0.352$ log points).

6. Quantification

In Table 7, we found that R&D and human capital have positive and statistically significant effects on rates of TFP growth through both innovation and technology transfer. But how economically important are these effects? The coefficients presented in Table 7 do not have a directly intuitive interpretation. In this Section, we investigate the quantitative importance of these variables in explaining TFP growth and changes in estimated steady-state relative TFP. We focus on total manufacturing to keep the results manageable.[45]

From equation (2.10), the total effect of R&D on TFP growth is composed of two terms: an effect on rates of innovation (ρ_1) and an effect on the speed of technology

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[45]The international trade interaction is only weakly significant in column (6) of Table 7. In this section, we therefore focus on the roles of R&D and human capital (the specification in column (3) of Table 7). We use our prefered TFP measure which is adjusted for hours worked and skills.

transfer $(-\delta_2.RTFP_{ijt-1})$. The second of these terms is the second 'face' of R&D, that we referred to earlier. Its magnitude depends on the level of relative TFP (on distance from the technological frontier). RTFP is zero for the frontier and negative for non-frontier countries. The more negative RTFP, the further a country lies behind the technological frontier, the greater the potential for technology transfer, and the greater R&D's contribution to TFP growth through technology transfer. The total effect of R&D on TFP growth will thus be greatest for the country furthest from the technological frontier. Exactly the same conclusions hold for human capital, which also affects TFP growth through both innovation (ρ_2) and technology transfer $(-\delta_3.RTFP_{ijt-1})$.

Table 9 evaluates the magnitude of each of these effects on TFP growth for each country in our sample. The parameters used are those shown in column (3) of Table 7. Column (1) of Table 9 reports the number of observations for which each country is the frontier (in any industry-year) out of the 1,822 observations that form the regression sample. In total, there are 217 observations on the frontier, of which the US is the frontier 86 times. The economy with the second highest number of frontier observations is Germany, with less than half the figure for the US. Column (2) reports, for each country, the average value of relative TFP ($t-1$) in total manufacturing during 1974-90. As noted above, this number is zero for the frontier and negative for non-frontier countries. It is in natural logarithms, so the exponent gives the average proportional relative TFP. In total manufacturing, the US is the frontier in 13 years and the Netherlands is the frontier country in 4 years.

Table 9: quantifying the effects of R&D and human capital

Country	(1) Frontier	(2) $\overline{RTFP}$	(3) R&D $\hat{\rho}_1 - (\hat{\delta}_2 \times \overline{RTFP})$	(4) Human Capital $\hat{\rho}_2 - (\hat{\delta}_3 \times \overline{RTFP})$
Canada	17	-0.191	0.572	0.315
Denmark	11	-0.318	0.679	0.373
Finland	0	-0.645	0.952	0.523
France	28	-0.164	0.549	0.303
Germany	34	-0.104	0.499	0.275
Italy	2	-0.363	0.716	0.394
Japan	25	-0.353	0.708	0.389
Netherlands	3	-0.100	0.496	0.274
Norway	0	-0.411	0.756	0.416
Sweden	5	-0.320	0.680	0.374
United Kingdom	7	-0.469	0.805	0.442
US	86	-0.006	0.417	0.231
$\hat{\rho}_1$	0.412			
$\hat{\rho}_2$	0.228			
$\hat{\delta}_1$	-0.023			
$\hat{\delta}_2$	-0.838			
$\hat{\delta}_3$	-0.457			

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 (3) of Table 7.

The bottom panel of Table 9 gives the estimated contribution of R&D and human capital to TFP growth (the ρ coefficients are the linear effect, while δ_2 and δ_3 are the coefficients on the interactions). In column (3) of Table 9, we evaluate the average total effect of R&D on rates of TFP growth in each country during 1974-90 (the sum of the contributions from innovation and technology transfer). Comparing the average total effect of R&D $(\hat{\rho}_1 - (\hat{\delta}_2 \times \overline{RTFP}))$ with the estimated contribution from innovation alone $(\hat{\rho}_1)$ reveals the relative importance for each country of the two faces of R&D. For the US, which is the frontier throughout most of the sample period, R&D's total effect (0.417) consists almost entirely of its effect on rates of innovation (0.412). For an economy such as Finland, whose average level of relative TFP in total

manufacturing during 1974-90 is just over 50%,[46] R&D's total effect (0.952) is more than twice as large as its effect on rates of innovation (0.412). Similarly, in column (4) we show the average total effect of human capital $(\hat{\rho}_2 - (\hat{\delta}_3 \times \overline{RTFP}))$. Again, for the US the full effect of human capital (0.231) consists almost entirely of the direct effect (0.228). Finland has the biggest effect from technology transfer (0.523 compared to 0.228).

One conclusion from the analysis above appears to be that the rate of return to R&D is higher in non-frontier countries. In these countries, R&D generates TFP growth through both innovation and technology transfer. In the frontier, R&D can only effect TFP growth through innovation. In so far as many existing (typically US-based) studies do not consider the role played by R&D in technology transfer, they will tend to underestimate the social rate of return to R&D in non-frontier countries.[47] However, it is important to distinguish between the social rate of return to R&D at the country level and the world level. Differentiating with respect to R&D intensity in the equation for frontier TFP growth (3.2), an increase by one unit in the R&D intensity results in a $(\hat{\rho}_1 \times 100\%)$ increase in frontier TFP growth. In steady-state, as discussed in Section 2, TFP in all countries grows at the same rate as in the frontier. Thus, as a result of technology transfer, an increase by one unit in the frontier R&D intensity raises TFP growth in *all countries* by $(\hat{\rho}_1 \times 100\%)$.[48]

The regression estimates in column (3) of Table 7 may also be used to derive implied steady-state levels of relative TFP. Extending equation (3.4) to incorporate an effect

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[46]The exponent of -0.645 is 52.5%.

[47]This conclusion receives independent support from the work of Eaton *et al.* (1998). They estimate a computable general equilibrium model of endogenous innovation and growth for 21 OECD countries. With the exception of Portugal, research productivity is found to be higher than in the United States (which is typically the frontier in our sample).

[48]This can be confirmed by differentiating with respect to frontier R&D in the equation for TFP growth in non-frontier countries, using the expressions for steady-state frontier TFP growth (3.2) and steady-state levels of relative TFP in non-frontier countries (3.4).

of human capital on both innovation and technology transfer, estimated steady-state relative TFP in sector j of a non-frontier country i is,

$$\ln\left(\frac{A_i}{A_F}\right)^*_{jt} = \frac{\hat{\psi}_{ij} + \hat{\rho}_1.\left(\frac{R}{Y}\right)_{ijt} + \hat{\rho}_2.H_{it} + T_t - (1 - \hat{\beta}_1).(\triangle\widehat{\ln A}_{Fjt})}{\hat{\delta}_1 + \hat{\delta}_2.\left(\frac{R}{Y}\right)_{ijt} + \hat{\delta}_3.H_{it}}. \qquad (6.1)$$

where, extending equation (3.2) to incorporate a role for human capital, the predicted rate of frontier TFP growth $(\triangle\widehat{\ln A}_{Fjt})$ is,

$$\triangle\widehat{\ln A}_{Fjt} = \hat{\psi}_{Fj} + \hat{\rho}_1.\left(\frac{R}{Y}\right)_{Fjt} + \hat{\rho}_3.H_{Ft} + T_t \qquad (6.2)$$

and estimated steady-state relative TFP for the frontier equals 1.

In analysing steady-state, we are concerned with long-run levels of relative TFP. Therefore, we evaluate estimated steady-state relative TFP using time-averaged values of the right-hand-side variables in equations (6.1) and (6.2).[49] Column (1) of Table 10 reports, for each country, the exponent of the time-average of relative TFP in total manufacturing during 1975-90 (as measured by the hours and skills adjusted superlative index). In column (2), we report the exponent of estimated steady-state relative TFP in total manufacturing during 1975-90 using the time-average of the right-hand-side variables in equations (6.1) and (6.2). The US is the frontier in total manufacturing throughout most of this period, and its estimated steady-state relative TFP is thus set equal to 1. Although there are some differences, estimated steady-state relative TFP typically lies close to mean actual relative TFP.

In columns (3) and (4) of Table 10, exactly the same analysis is undertaken for first half of the period (1975-82). The US is the frontier throughout this period, and

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[49]An alternative is, clearly, to evaluate relative TFP in each year of the sample using contemporaneous values of the right-hand-side variables and average relative TFP over time for each country-industry. The results of implementing this procedure are qualitatively the same. We adopt the method in the text to facilitate a decomposition of changes in steady-state relative TFP into the contributions of R&D and human capital. We exclude the first year of the sample from the ensuing analysis, since 1975-90 can be divided into the two equally-sized sub-periods 1975-82 and 1983-90.

its estimated steady-state relative TFP is again set equal to 1. Columns (5) and (6) repeat the analysis for 1983-90, where estimated steady-state relative TFP in the US is again set equal to 1.

Actual relative TFP will depart from its steady-state value if there are changes in the independent variables or non-zero stochastic errors (ε_{ijt} and ε_{Fjt}) on the right-hand side of equations (3.2) and (3.1). During 1975-82, we find evidence of larger departures between estimated steady-state and actual relative TFP, although, for some countries, the two variables remain close together. In general, during 1983-90, estimated steady-state and actual relative TFP lie close together. One possible reason for the worse performance of our model in the 1975-82 period is the presence of the OPEC oil shocks in 1974 and 1979.

Table 10: exponent of actual and estimated steady-state relative TFP in total manufacturing

	(1)	(2)	(3)	(4)	(5)	(6)
	1975-90		1975-82		1983-90	
Country	Actual	Steady-state	Actual	Steady-state	Actual	Steady-state
Canada	0.83	0.91	0.84	0.88	0.81	0.94
Denmark	0.74	0.66	0.73	0.62	0.74	0.70
Finland	0.53	0.54	0.48	0.44	0.59	0.63
France	0.86	0.76	0.83	0.67	0.89	0.83
Germany	0.91	0.70	0.90	0.63	0.92	0.75
Italy	0.71	0.73	0.65	0.62	0.77	0.82
Japan	0.71	0.68	0.68	0.59	0.74	0.77
Netherlands	0.92	0.87	0.86	0.81	0.98	0.92
Norway	0.66	0.57	0.67	0.49	0.66	0.65
Sweden	0.73	0.72	0.71	0.64	0.75	0.79
UK	0.63	0.64	0.60	0.61	0.66	0.66
US	0.99	1	1	1	0.99	1

Note: actual relative TFP is the time-average during 1975-90, 1975-82, or 1983-90. Steady-state relative TFP is derived from equations (6.1) and (6.2) using time-averaged values of right-hand-side variables.

Using equations (6.1) and (6.2), it is possible to decompose changes in estimated steady-state relative TFP into the contributions of changes in R&D and changes in human capital. This is done in Table 11. In column (1) we evaluate the logarithmic growth in estimated steady-state relative TFP between the two sub-periods, expressed as an annual percentage rate of growth for the seven years separating the mid-points of each sub-period. We saw in Section 4 of the paper that the sample period was one of convergence in levels of relative TFP, and this is reflected in Table 11 in a positive rate of growth in steady-state relative TFP in all countries. The rate of growth varies across countries, with Finland, Italy, and Japan exhibiting large increases in steady-state relative TFP, and Canada and the UK displaying the smallest changes among non-frontier countries. Column (2) reports the annual percentage rate of growth in estimated steady-state relative TFP induced by allowing R&D to change between the first and second sub-periods, but holding human capital constant at its value in the first sub-period. Note that the rates of growth reported in Table 11 are the net effect of changes in R&D in both frontier and non-frontier countries. Column (3) presents the results of undertaking the same exercise for human capital, holding R&D constant at its value in the first sub-period. From equations (6.1) and (6.2), it is clear these two columns do not necessarily sum to the annual percentage rate of growth in steady-state relative TFP when both R&D and human capital change (column (1)), although, in practice, the differences between column (1) and the sum of columns (2) and (3) are relatively small.

Table 11: annual growth in estimated steady-state relative TFP between 1975-82 and 1983-90, and the contributions of R&D and human capital

Country	(1) Change (%)	(2) R&D (%)	(3) Human Capital (%)	(4) R&D (share (%))	(5) Human Capital (share (%))
Canada	1.3	0.2	1.1	16.8	83.2
Denmark	2.6	0.9	1.9	30.8	69.2
Finland	6.0	2.6	4.4	37.1	62.9
France	4.0	1.5	3.1	31.8	68.2
Germany	3.3	1.6	2.1	43.4	56.6
Italy	5.5	1.8	4.6	27.8	72.2
Japan	4.6	2.1	3.2	39.0	61.0
Netherlands	2.7	2.3	0.7	24.5	75.5
Norway	4.9	2.2	3.3	40.3	59.7
Sweden	3.7	1.8	2.4	43.4	56.6
UK	1.9	0.4	1.6	19.5	80.5
US	0	0	0	-	-

Notes: columns (2) and (3) do not necessarily sum to column (1), although, in practice, the difference is not large. Columns (4) and (5) are the percentage contributions of R&D and human capital to the sum of columns (2) and (3).

In the final two columns of Table 11, we report the percentage share of R&D and human capital's contributions in the sum of columns (2) and (3). Changes in human capital are, in general, responsible for most of total change in estimated steady-state relative TFP implied by columns (2) and (3). However, there are substantial differences across countries in the relative importance of R&D and human capital. For example, in Canada 83.2% of the total change in estimated steady-state relative TFP is explained by changes in human capital and 16.7% by changes in R&D. In Germany and Sweden, 56.6% of the total change in estimated steady-state relative TFP is explained by changes in human capital and 43.4% by changes in R&D.

7. Conclusions

This paper has produced econometric evidence for the importance of the "two faces of R&D" by examining the determinants of productivity growth in 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. In particular, we also identified a role for human capital in stimulating innovation and absorptive capacity. By contrast, trade had a statistically weak effect on technology transfer and no impact on innovation.

In addition to statistical significance, these effects are quantitatively important. In general, human capital explains most of the increase in estimated steady-state relative TFP in OECD countries between 1975-82 and 1983-90. However, there are substantial cross-country differences in the relative importance of R&D and human capital, and the R&D's contribution remains substantial (43% in Sweden and Germany).

An implication of the results is that the world-wide social returns to investing in R&D and human capital are underestimated in studies which focus solely on the US economy, since the US is the technological frontier for a large number of industries. There is an important spillover at the world level from frontier to non-frontier countries. As a result of technology 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? The incentive to invest in R&D is determined by the private return and not the social return, however. R&D may be

held back in many non-Frontier countries by under-development of financial markets or inappropriate government policies, for example. A future research agenda should be to investigate these issues, through using firm 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.

Other avenues for future work would be to extend our framework to allow economies to learn from non-frontier countries and also 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.

<Figure 1 here>

<Figure 2 here>

<Figure 3 here>

Appendix A: Data Appendix

A.1. Data sources

We constructed our panel dataset by combining several sources.

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 available 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,

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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 analysed extensively by other authors (e.g. Berman, Bound and Machin, 1998) who have found the occupational split 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.

Industry-Specific Purchasing Power Parities (PPPs): the ISDB data uses a whole-economy output PPP to convert real value-added to a common currency (1990 dollars). Industry-specific output PPPs for 36 three and four-digit ISIC manufacturing

industries were taken from Pilat (1996). Data are available for the following countries: Canada, France, Germany, Japan, Netherlands, Sweden, United Kingdom, and United States. For those countries where industry-specific PPP data is not available, we adjust the whole economy PPP by the average ratio across countries of the industry-specific to the whole economy PPP in a particular industry.

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 US). These numbers are available only for France, Germany, Japan, Sweden, U.K., and the US

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 constructed 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 (1998) 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's (1995) 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 ((4.1) and (4.3)) 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.2.4. Industry specific PPPs

Relative TFP is constructed using a whole-economy PPP to convert constant (1985) price data on value added and physical capital into a common currency (US dollars), while labour input is measured in common units of employment. We follow a number of existing studies in using a whole economy-PPP to construct our baseline measure of relative TFP.[50] The main alternative is to use industry-specific PPPs for the value-added of individual manufacturing industries.[51] Therefore as a robustness test, we use the disaggregated industry-specific PPPs available for 7 OECD countries in our sample (Canada, France, Germany, Netherlands, Sweden, United Kingdom, and United States) in Pilat (1996). These are aggregated up to the industry classification in ISDB using value-added shares. For those countries where industry-specific PPP data is not available, we adjust the whole economy PPP by the average ratio across countries of the industry-specific to the whole economy PPP in a particular industry.

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[50]See in particular Dollar and Wolff (1994), Bernard and Jones (1996a,b) and Harrigan (1997).

[51]See for example van Ark and Pilat (1993), Pilat (1996), and Jorgenson and Kuroda (1990). Physical capital is assumed to be relatively mobile across sectors. Hence a single PPP is used for physical capital in all sectors (ISDB, KTVD).

Appendix B: Further Econometric Estimates

Table B1: TFP growth equation (excluding frontier)

ΔTFP_{ijt}	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Obs	1745	1745	1745	186	1728	1553	1568	1576	1584
Years	75-92	75-92	75-92	75-92	75-92	75-90	75-90	75-90	75-90
ΔTFP_{Fjt}	0.179	0.175	0.180	0.292	0.209	0.175	0.159	0.146	0.134
	0.027	*0.027*	*0.028*	*0.086*	*0.034*	*0.033*	*0.031*	*0.034*	*0.030*
$RTFP_{ijt-1}$	-0.029	-0.086	-0.100	-0.131	-0.090	-0.101	-0.087	-0.092	-0.083
	0.005	*0.014*	*0.017*	*0.035*	*0.015*	*0.016*	*0.015*	*0.013*	*0.012*
Year dummies	yes	yes	yes		yes	yes	yes	yes	yes
Within groups		yes	yes	yes	yes	yes	yes	yes	yes
IV			yes						
Total manufacturing				yes					
Adjustments to TFP									
Hours adjustment					yes	yes	yes	yes	yes
Skills adjustment						yes	yes	yes	yes
Markup							yes	yes	yes
Capacity utilisation								yes	yes
PPP									yes

Notes: numbers in italics are robust standard errors; instrument for $RTFP_{ijt-1}$ in column (3) is $RTFP_{ijt-2}$. Weighted Least Squares using industry shares of total manufacture employment.

Table B2: impact of R&D on TFP growth equation (excluding frontier)

ΔTFP_{ijt}	(1)	(2)	(3)	(4)	(6)	(7)	(8)	(9)
Obs	1745	1745	1745	1557	1553	1568	1576	1584
Years	75-92	75-92	75-92	75-92	75-90	75-90	75-90	75-90
ΔTFP_{Fjt}	0.175	0.167	0.166	0.178	0.160	0.147	0.129	0.116
	0.027	*0.027*	*0.027*	*0.028*	*0.032*	*0.030*	*0.033*	*0.030*
$RTFP_{ijt-1}$	-0.086	-0.091	-0.072	-0.094	-0.085	-0.070	-0.073	-0.071
	0.014	*0.014*	*0.015*	*0.016*	*0.018*	*0.018*	*0.016*	*0.015*
$(R/Y)_{ijt-1}$	-	0.509	0.319	0.593	0.580	0.565	0.412	0.377
		0.167	*0.205*	*0.222*	*0.222*	*0.209*	*0.178*	*0.197*
$(RTFP*(R/Y))_{ijt-1}$	-	-	-0.562	-0.346	-0.822	-0.957	-0.959	-0.770
			0.356	*0.359*	*0.376*	*0.366*	*0.355*	*0.267*
Year dummies	yes	yes	yes	yes	yes	yes	yes	yes
Within groups	yes	yes	yes	yes	yes	yes	yes	yes
Adjustments to TFP								
Skills Adjustment				yes	yes	yes	yes	yes
Hours					yes	yes	yes	yes
Markup						yes	yes	yes
Capacity utilisation							yes	yes
PPP								yes

Notes: numbers in italics are robust standard errors. Weighted Least Squares - weights are shares of total manufacture employment.

Table B3: impact of R&D, trade, and human capital on TFP growth (excl fron)

ΔTFP_{ijt}	(1)	(2)	(3)	(4)	(5)	(6)
Obs	1553	1553	1553	1553	1553	1553
Years	75-90	75-90	75-90	75-90	75-90	75-90
Trade Variable (trade with:)				Frontier	Frontier	Frontier
ΔTFP_{Fjt}	0.160	0.159	0.159	0.161	0.157	0.156
	0.032	0.033	0.032	0.033	0.032	0.032
$RTFP_{ijt-1}$	-0.085	-0.080	-0.037	-0.088	-0.089	-0.044
	0.018	0.018	0.024	0.018	0.018	0.024
$(R/Y)_{ijt-1}$	0.580	0.486	0.556	0.594	0.642	0.597
	0.222	0.218	0.213	0.222	0.224	0.216
$(RTFP*(R/Y))_{ijt-1}$	-0.822	-0.977	-0.658	-0.790	-0.667	-0.566
	0.376	0.383	0.382	0.378	0.383	0.385
H_{it-1}	-	0.403	0.248	-	-	0.283
		0.145	0.136			0.136
$(RTFP*H)_{it-1}$	-	-	-0.502	-	-	-0.458
			0.150			0.154
$(IMPS/Y)_{ijt-1}$	-	-	-	0.020	-0.003	0.003
				0.008	0.014	0.011
$(RTFP*(IMPS/Y))_{ijt-1}$	-	-	-	-	-0.089	-0.068
					0.034	0.034
Year dummies	yes	yes	yes	yes	yes	yes
Within groups	yes	yes	yes	yes	yes	yes
Skills Adjustment	yes	yes	yes	yes	yes	yes
Hours	yes	yes	yes	yes	yes	yes

Notes: numbers in italics are robust standard errors. Weighted Least Squares using industry shares of total manufacture employment.

In Table B4 we examine the robustness of our preferred specification column (5) in Table 6. In columns (1) and (2) we implement a model with longer dynamics (an ADL(2,2) specification). The first column includes a lagged dependent variable, the lagged frontier growth rate and the TFP gap in t-2. The second column then also includes R&D intensity at t-2 and its interaction with the GAP. The R&D level and interaction terms are both correctly signed and significant at conventional levels. The next two columns experiment with using R&D stocks rather than R&D flows. Column (3) simply replaces the flow with the stock. Column (4) uses the change in the stock, a specification consistent with equation (2.3) when the R&D depreciation rate is not small (15% in this case). Although the R&D terms are signed as before, they are less precisely determined. In column (4), only the R&D interaction term is significant at conventional critical values, which may reflect the difficulty of choosing the appropriate level of the knowledge depreciation parameter.

Table B4: robustness (including frontier)

ΔTFP_{ijt}	(1) Longer Dynamics	(2)	(3) R&D Stock	(4)
Obs	1716	1716	1822	1716
Years	76-90	76-90	75-90	75-90
ΔTFP_{Fjt}	0.118	0.109	0.116	0.122
	0.031	*0.031*	*0.030*	*0.031*
$\triangle TFP_{Fjt-1}$	0.083	0.078	-	-
	0.028	*0.028*		
$\triangle TFP_{ijt-1}$	-0.065	-0.089	-	-
	0.034	*0.034*		
$RTFP_{ijt-2}$	-0.094	-0.065	-	-
	0.017	*0.018*		
$(R/Y)_{ijt-1}$	-	-	-	-
$(R/Y)_{ijt-2}$	-	0.442	-	-
		0.195		
$(RTFP*(R/Y))_{ijt-2}$	-	-1.256	-	-
		0.364		
$RTFP_{ijt-1}$	-	-	-0.068	-0.079
			0.017	*0.017*
$(RTFP*(R/Y))_{ijt-1}$	-	-	-	-
$(G/Y)_{ijt-1}$	-	-	0.144	-
			0.047	
$(RTFP*(G/Y))_{ijt-1}$	-	-	-0.212	-
			0.085	
$(\Delta G_{ijt-1})/Y_{ijt-1}$	-	-	-	0.208
				0.285
$RTFP*(\Delta G_{ijt-1})/Y_{ijt-1}$	-	-	-	-1.180
				0.651
Year dummies	yes	yes	yes	yes
Within groups	yes	yes	yes	yes
Skills Adjustment	yes	yes	yes	yes
Hours	yes	yes	yes	yes

Notes: numbers in italics are robust standard errors; estimation by Weighted Least Squares with industry shares of a country's total manufacturing employment in 1970 as weights.

Appendix C: Two Faces of R&D in a General Equilibrium Model of Endogenous Innovation

This Appendix presents a general equilibrium model of endogenous innovation growth, in which research and development (R&D) activity is the source of long-run TFP growth. The majority of the existing theoretical literature emphasises the links between R&D and *innovation*. One of the seminal theoretical models is Aghion and Howitt (1992), and we begin by presenting an overlapping generations version of this model, in which uncertain R&D investments result in improvements in the quality or productivity of existing goods.[52] An equation for the rate of TFP growth is derived, in which investments in R&D have a direct effect on productivity growth. The point is made most clearly in a model with many countries and one industrial sector; a later section of the Appendix extends the analysis to many industrial sectors.

A less developed strand of the literature on R&D and technological progress considers the idea that R&D expenditure facilitates the imitation or adoption of technologies discovered by other economic agents. The informal literature frequently argues that technological transfer depends upon firms' 'absorptive capacity' or 'tacit knowledge', and we extend the overlapping generations model above to allow R&D expenditure to promote absorptive capacity and enable the transfer of technology.[53] A modified equation for the rate of TFP growth is derived, in which R&D activity affects productivity both directly and indirectly in the form of an interaction term between R&D and the gap from the technological frontier. Again the point is made first with a single industrial sector; the analysis is then extended to the multi-sector case.

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[52] A similar modelling structure is used by Redding (1999) to explore the idea that technological change is inherently *path dependent*.

[53] For alternative theoretical models in which R&D plays a role in both innovation and imitation, see Cohen and Levinthal (1989), Grossman and Helpman (1991), Neary and Leahy (1999), and Segerstrom (1991).

C.1. R&D and innovation

Consider a world of a number of countries, indexed by $i = 1, ..., N$. Each country is populated by a sequence of overlapping generations, indexed by $t \in [1, \infty]$. We choose units, such that t also indexes time. Generations consist of a large number of representative agents L, each of whom lives for two periods. There are three sectors of economic activity: final goods production, intermediate input production, and research.

Final goods are produced with intermediate inputs. We begin by considering the case where there is only one final good, manufactured from the output of a single intermediate goods sector. A later section extends the analysis to allow many final goods, each of which is produced from the output of its own intermediate goods sector. Labour is the sole primary factor of production and is used to produce intermediate inputs. Technological change is modelled as improvements in the quality or productivity of intermediate inputs.

The timing of agents' decisions is as follows. At the beginning of the first period (when 'young'), agents inherit a stock of existing technology from the preceding generation and decide whether to enter research or intermediate input production. Those who enter the intermediate goods sector produce intermediate inputs in periods one and two. For those who enter the research sector, period one is spent engaged in uncertain R&D. All research uncertainty is resolved at the end of period one. In the case of successful research, a new technology for intermediate input production may be employed in period two (when 'old'). Otherwise, the existing technology for intermediate input production continues to be employed.

C.1.1. Consumer behaviour

The representative agent in each generation is endowed with one unit of labour, which is supplied inelastically with zero disutility. Consumer preferences are defined over consumption of the final good. Agents are assumed to be risk neutral, and hence utility is linear in each period's consumption of the final good.

$$U_{it} = c_{i1t} + \left(\frac{1}{1+\rho} \right).c_{i2t} \tag{C.1}$$

where c_{ikt} denotes period k consumption and ρ denotes the subjective rate of time discount.

C.1.2. Production and technology

Output of an homogenous final good (y_{it}) is produced from an intermediate input (x_{it}) according to a Cobb-Douglas technology,

$$y_t = A_{it}.x_{it}^{\alpha}, \qquad 0 < \alpha < 1 \tag{C.2}$$

where A_{it} denotes the productivity or quality of intermediate inputs. Final goods output is assumed to be tradeable at zero transport cost, while intermediate inputs and labour are assumed to be non-tradeable. Final goods production is assumed to occur under conditions of perfect competition, and we choose the final good for numeraire $(p_t = 1$ for all $t)$.

Intermediate goods technologies are indexed by $m = 0, 1, ...$, which denotes the interval starting with the mth innovation and ending with the $m+1^{\text{st}}$. Following Aghion and Howitt (1992), each innovation is assumed to raise the quality or productivity of the existing technology by a constant proportion $\gamma > 1$. The state of technology in economy i at time t may be indexed by m alone and is simply $A_{im} = \gamma^m.A_i(0)$, where we normalise $A_i(0)$ to 1.[54] Intermediate inputs themselves are produced with labour

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[54]In order to simplify notation, we suppress the implicit dependence of m upon i and upon t.

according to a constant returns to scale technology,

$$x_{it} = l_{it}, \tag{C.3}$$

where $l_{it} = L - n_{it}$ denotes the number of agents in generation t who choose to enter intermediate production and n_{it} the corresponding number who undertake research.

C.1.3. Research technology

The specification of research is a discrete time version of that in Aghion and Howitt (1992). Research is an inherently uncertain process. Each of the n_{it} individuals is assumed to innovate with probability λ (where $0 < \lambda < 1$); if more than one individual innovates, the patent to the new fundamental technology $(m+1)$ is allocated randomly among the n_{it} researchers. The probability that any one individual receives the patent is thus,

$$\Lambda(n_{it}) \equiv \frac{1}{n_{it}} \left[1 - (1 - \lambda)^{n_{it}} \right] \tag{C.4}$$

where the aggregate probability that a new technology is discovered is simply $\Lambda(n_{it}).n_{it}$.

C.1.4. General equilibrium

In an equilibrium in which both research and intermediate production occur in positive amounts, we require that agents are indifferent between the two activities. We begin by considering the returns to research. With probability $\Lambda(n_{it})$, an individual researcher receives the patent to the next technology $m+1$. With the constant returns to scale technology (C.3), the flow of profits from employing the new technology in intermediate production when old is,

$$\pi_{i2t,m+1} = [q_{i2t,m+1} - w_{i2t}].(L_i - n_{it}) \tag{C.5}$$

where $q_{i2t,m+1}$ denotes the price of intermediate inputs of quality $m + 1$ and w_{i2t} the wage received when old by those entering intermediate input production.

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The equilibrium wage (w_{i2t}) is determined by bargaining between the successful researcher and the $(L - n_{it})$ individuals who chose to enter intermediate production. The latter retain the outside option of producing intermediate inputs with the next most advanced technology (m), and therefore the successful researcher will make a 'take it or leave it' offer of a wage w_{i2t} exactly equal to the return from employing that technology. This return is obtained from the inverse demand function for intermediate inputs of a given quality or productivity A. From the final goods technology (C.2), we have,

$$w_{i2t} = q_{i2t,m} = \alpha.A_{im}.x_{it}^{\alpha-1} = w_{i1t} = w_{it} \qquad (C.6)$$

The successful researcher's profit maximisation problem in equation (C.5) now reduces to choosing $q_{i2t,m+1}$ maximise profits, given the wage w_{i2t} and the number of individuals $(L - n_{it})$ who chose to enter the intermediate goods sector. The flow of profits from intermediate production will be maximised by charging the highest price $q_{i2t,m+1}$ consistent with final goods producers being willing to employ intermediate inputs produced with the new technology $m+1$. The equilibrium price $q_{i2t,m+1}$ therefore takes the form of a limit price that leaves final goods producers indifferent between employing technologies $m + 1$ and m. This limit price may be obtained from the cost function dual to the final goods production technology. With a Cobb-Douglas final goods technology, we have,

$$q_{i2t,m+1} = \gamma^{1/\alpha}.w_{it}, \qquad (C.7)$$

From equations (C.4), (C.5), and (C.7), the lifetime expected returns from research are thus,

$$V_{it}^r = \left(\frac{1}{1+\rho}\right).\Lambda(n_{it}).\left[\gamma^{1/\alpha} - 1\right].w_{it}.(L - n_t) \qquad (C.8)$$

where, since $\Lambda(n_{it})$ is monotonically decreasing in n_{it}, the whole expression V_{it}^r is monotonically decreasing in n_{it}.

When young, each individual faces a choice between entering research and intermediate input production. From the above, the lifetime expected returns from choosing to produce intermediate inputs is,

$$V_{it}^p = \left(1 + \frac{1}{1+\rho} \right) . w_{it} \qquad (C.9)$$

In a general equilibrium characterised by positive amounts of research and production, we require that agents are indifferent between the two activities. The equilibrium level of employment in research $(\hat{n}_{it})$ therefore solves,

$$2 + \rho = \Lambda(n_{it}). \left[\gamma^{1/\alpha} - 1 \right] . (L_i - n_{it}) \qquad (C.10)$$

where the left and right-hand sides of the equation may be interpreted as the private marginal cost and marginal benefit of research respectively.

C.1.5. Final output growth

From equation (C.2), the economy's expected rate of growth between the first and second period's of generation t depends only on the expected rate of growth in the quality or productivity of intermediate inputs. From the specification of research above, it follows that the expected rate of growth of labour productivity (which in this case is equal to the expected rate of growth of TFP) is simply,

$$\zeta_{it}^e = \mathsf{E}_t \ln \left(\frac{y_{i2t}}{y_{i1t}} \right) = \left[1 - (1 - \lambda)^{n_{it}} \right] . \ln \gamma \qquad (C.11)$$

Since $0 < \lambda < 1$, the economy's expected rate of growth is monotonically increasing in equilibrium research employment. As in the econometric analysis, this suggests a specification for productivity growth in which measures of R&D activity have a direct effect on rates of TFP growth.

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C.2. R&D and technology transfer

In the main body of the paper, it was argued that technology transfer provides an important additional source of productivity growth for non-frontier economies. We begin by extending the framework above to allow technology transfer to occur independently of profit-seeking investments in R&D. The next section introduces an explicit role for R&D in the process of technology transfer.

The main structure of the model is exactly as before. At the beginning of period one, agents choose whether to engage in research or intermediate production. Research takes one period and all research uncertainty is resolved at the end of period 1. Technology transfer is also assumed to take place in period 1, so that the quality or productivity of the final goods technology is higher in period two than in period one independently of whether or not research is successful. Specifically, we assume that, as a result of technology transfer, productivity rises by the proportion $Q(A_{Fm}/A_{im})$,[55]

$$A_{im+1} = Q(A_{Fm}/A_{im}).A_{im} \tag{C.12}$$

We impose the following restrictions on the function $Q(A_{Fm}/A_{im})$,

$$Q(1) = 1, \qquad Q'(\cdot) > 0, \qquad Q''(\cdot) < 0$$

For simplicity, we assume a constant elasticity functional form,

$$Q(A_{Fm}/A_{im}) = (A_{Fm}/A_{im})^{\mu}, \qquad 0 < \mu < 1$$

The transferred technology spills over to all agents in the non-frontier economy. In the event of unsuccessful research, intermediate input production will occur under conditions of perfect competition with technology $A_{im+1} = (A_{Fm}/A_{im})^{\mu}.A_{im}$. The specification of the innovation process is directly analogous to before. Each innovation

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[55]Again, we suppress the implicit dependence of m on i and t.

raises the quality or productivity of the final goods technology by a proportion $\gamma > 1$ above the level otherwise achieved through technology transfer alone,[56]

$$A_{im+1} = \gamma.(A_{Fm}/A_{im})^\mu.A_{im} \qquad (C.13)$$

The existence of technology transfer changes the outside option of workers in the intermediate goods sector. Workers outside option in period two is to employ technology of quality $A_{im+1} = (A_{Fm}/A_{im})^\mu.A_{im}$ and the equilibrium second period wage paid by a successful researcher is thus,

$$w_{i2t} = \alpha.(A_{Fm}/A_{im})^\mu.A_{im}.x_t^{\alpha-1} = (A_{Fm}/A_{im})^\mu.w_{i1t}$$

However, the limit price that leaves final goods producers indifferent between employing the innovation (of productivity $\gamma.(A_F/A_m)^\mu$) and the existing technology augmented by technology transfer (of productivity $(A_F/A_m)^\mu$) is unchanged,

$$q_{m+1,2t} = \gamma^{1/\alpha}.w_{i2t}$$

The expression for profits is unchanged, but must now take into account the fact that the wage in the intermediate sector rises between periods 1 and 2 as a result of technology transfer. The no-arbitrage condition between research and intermediate production is therefore,

$$\left[\frac{1+\rho}{(A_{Fm}/A_{im})^\mu} \right] + 1 = \Lambda(n_t).\left[\gamma^{1/\alpha} - 1 \right].(L_i - n_{it})$$

In an equilibrium with positive research employment, the equation for the expected rate of growth of TFP is now given by,

$$\zeta_{it}^e = \mathsf{E}_t \ln\left(\frac{y_{i2t}}{y_{i1t}} \right) = \left[1 - (1-\lambda)^{n_{it}} \right].\ln\gamma + \mu.\ln(A_{Fm}/A_{im}) \qquad (C.14)$$

As in the econometric estimation, the equation for TFP growth includes a direct effect of R&D activity and a term in the size of the technological gap from the frontier.

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[56]Implicitly, we assume that researchers have access to the technology transferred during period one. Innovations build upon this knowledge and raise productivity by a constant proportion above the level achieved through technology transfer.

C.3. Two faces of R&D: innovation and technology transfer

This section introduces a role for R&D in facilitating technology transfer. Following Aghion and Howitt (1997) Chapter 2, we extend the analysis to allow the size of innovations to be a function of an economy's distance from the technological frontier. The specification of the innovation process is exactly as above, except that we assume an innovation raises the quality or productivity of intermediate inputs by the proportion $\Gamma(A_{Fm}/A_{im})$. We impose the following restrictions on the function $\Gamma(A_{Fm}/A_{im})$,

$$\Gamma(1) = 1, \qquad \Gamma'(\cdot) > 0, \qquad \Gamma''(\cdot) < 0$$

For simplicity, we again assume a constant elasticity functional form,

$$\Gamma(A_{Fm}/A_{im}) = \gamma.(A_{Fm}/A_{im})^{\phi}, \qquad 0 < \phi < 1, \ \gamma > 1$$

In the absence of innovation, the rise in productivity through technology transfer alone is exactly as specified in equation (C.12). If research is successful, the level of productivity following the innovation is given by,

$$A_{im+1} = \gamma.(A_{Fm}/A_{im})^{\phi+\mu}.A_{im} \tag{C.15}$$

Workers' outside option in period two remains unchanged, but the limit price that leaves final goods producers indifferent between the innovation and the existing technology augmented by technology transfer is now given by,

$$q_{i2t,m+1} = \gamma^{1/\alpha}.(A_{Fm}/A_{im})^{\phi/\alpha}.w_{i2t}$$

As a result, the no-arbitrage condition between research and intermediate production becomes,

$$\left[\frac{1+\rho}{(A_{Fm}/A_{im})^{\mu}}\right] + 1 = \Lambda(n_{it}).\left[\gamma^{1/\alpha}.(A_{Fm}/A_{im})^{\phi/\alpha} - 1\right].(L_i - n_{it})$$

In an equilibrium characterised by positive research employment, the equation for the expected rate of growth of TFP is given by,

$$\zeta_{it}^e = \mathsf{E}_t \ln \left(\frac{y_{i2t}}{y_{i1t}} \right) = [1 - (1 - \lambda)^{n_{it}}] \, . \, [\ln \gamma + \phi . \ln(A_{Fm}/A_{im})] + \mu . \ln(A_{Fm}/A_{im}) \tag{C.16}$$

The equation for TFP growth now includes a term in the technology gap, a term for the direct effect of R&D on TFP growth, and an interaction term between R&D activity and the size of the technological gap.

C.4. Multi-sectors

The preceding sections have derived an equation for TFP growth in a single sector general equilibrium model of endogenous innovation, which takes the same form as that employed in the econometric estimation. In this section, the analysis is extended to the multi-sector case. Lifetime utility is the discounted sum of instantaneous utilities,

$$U_{it} = u_{i1t} + \frac{1}{1 + \rho} . u_{i2t} \tag{C.17}$$

Instantaneous utility is defined over the consumption of J final goods, indexed by $j = 1, ..., J$. For simplicity, we assume these goods are perfect substitutes and the instantaneous utility function thus takes the form,

$$u_{i1t} = \sum_{j=1}^{J} c_{i1jt} \tag{C.18}$$

The equilibrium price of each final good (p_{ijt}) is determined by the requirement that price equal marginal utility,

$$p_{ijt} = 1, \qquad \forall j \tag{C.19}$$

Units of each final good are homogeneous and we assume that all final goods are tradeable at zero transport cost. The production technology for each final good j is

as specified in equation (C.2), and hence the derived demand for intermediate inputs of productivity A_{ijm} takes exactly the same form as before,

$$q_{ijt,m} = \alpha . A_{ijm} . x_{ijt}^{\alpha-1} \tag{C.20}$$

Denote the number of individuals who choose to enter *either* research *or* intermediate production in sector j by $L_{ij} = l_{ijt} + n_{ijt}$. The general equilibrium allocation of labour to intermediate production and research in each sector j of economy i is determined by three sets of conditions. First, we require that the L_{ij} agents in sector j are indifferent between research and intermediate production in that sector. This no-arbitrage condition is directly analogous to that in the single sector model. In the most general model with technology transfer and both an innovative and imitative role for R&D, we obtain,

$$\left[\frac{1+\rho}{(A_{Fjm}/A_{ijm})^{\mu}} \right] + 1 = \Lambda(n_{ijt}) . \left[\gamma^{1/\alpha} . (A_{Fjm}/A_{ijm})^{\phi/\alpha} - 1 \right] . (L_{ij} - n_{ijt}) \tag{C.21}$$

For any total allocation of labour to sector j (L_{ij}), this equation determines equilibrium employment in research in sector j $(\hat{n}_{ijt})$. The second and third sets of conditions pin down the equilibrium total allocation of labour to sector j $(\hat{L}_{ij})$. The second condition is that the expected return from intermediate input production is equal in any two sectors j and h,

$$V_{ijt}^{p} = V_{iht}^{p}, \qquad \forall j, h$$

$$\left(1 + \frac{(A_{Fjm}/A_{ijm})^{\mu}}{1+\rho} \right) . w_{ij1t} = \left(1 + \frac{(A_{Fjm}/A_{ijm})^{\mu}}{1+\rho} \right) . w_{ih1t}, \qquad \forall j, h \tag{C.22}$$

where the period one wage w_{ij1t} is determined by the return to employing the final goods technology inherited by generation t in sector j of economy i (see equation (C.20)). The third condition is that the labour market clear,

$$\sum_{j=1}^{J} L_{ijt} = L_i \tag{C.23}$$

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Taking equations (C.21) and (C.22) for each sector j, and combining them with the labour market clearing condition (C.23), yields a system of $2J+1$ equations, which may be used to solve for the $2J$ unknowns $\{\hat{n}_{ijt}, \hat{L}_{ijt}\}$ in economy i. If we consider the most general model, with technology transfer and two roles for R&D, the expected rate of TFP growth in sector j of economy i is then simply,

$$\zeta_{ijt}^{e} = \mathsf{E}_t \ln \left(\frac{y_{ij2t}}{y_{ij1t}} \right) = \left[1 - (1-\lambda)^{n_{ijt}} \right] . \left[\ln \gamma + \phi . \ln(A_{Fjm}/A_{ijm}) \right] + \mu . \ln(A_{Fjm}/A_{ijm})$$

which is directly analogous to the econometric equation in our empirical analysis.

Executive Summary

Many writers have claimed that 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 of the technological frontier (this is sometimes known as 'absorptive capacity'). Arrow (1969) quotes the example of 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. Technological spillovers are not automatic, it requires an investment in education and research to adapt the advances of others to your own use. Despite anecdotal evidence for this idea, there is little quantitative evidence of its importance. In this paper we seek to provide evidence of the importance of the dual nature of R&D in explaining the fortunes of several industries within OECD countries over two decades.

First, we document that there has been convergence of TFP within a panel of industries across thirteen OECD countries since 1970. Furthermore, we find evidence that both R&D and human capital appear statistically and economically important in this catch-up process as well as in stimulating innovation directly. Countries which are behind the technological frontier grow more quickly if they invest in R&D and human capital. This is consistent with the view that knowledge accumulation benefits a country through enabling it to dip into the pool of knowledge. Trade, by contrast, plays a more modest role in productivity growth. These results are robust to a large variety of statistical tests and provide some of the first hard evidence for the importance of the 'second face of R&D'. We also find that social returns to R&D are underestimated by most studies which concentrate upon the US economy.

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