Sources of Knowledge and Productivity: How Robust is the Relationship?

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SOURCES OF KNOWLEDGE AND PRODUCTIVITY: HOW ROBUST IS THE RELATIONSHIP?

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ABSTRACT

We estimate domestic productivity relationships for a sample of 16 OECD countries through probably the most general specification yet. We identify ten key determinants of productivity - all derived from different theoretical models. Our specification may address the potential problem of omitted variables. The issues of cross-country heterogeneity and endogeneity are addressed. The sources of knowledge appear robust in driving productivity; however, other determinants postulated by different theoretical models are also significant. The productivity relationships are heterogeneous across OECD countries implying that country-specific factors may play an important role in domestic productivity policy.

JEL Classification: F12; F2: O3; O4; C15

Key Words: Sources of Knowledge; Dynamic Heterogeneity; MFP; Methods of Moments.

QUELLE EST LA ROBUSTESSE DE LA RELATION ENTRE SOURCES DE CONNAISSANCES ET PRODUCTIVITÉ ?

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RÉSUMÉ

Nous estimons des relations concernant la productivité intérieure pour un échantillon de 16 pays de l'OCDE, en utilisant une spécification qui est probablement la plus générale ayant été employée jusqu'ici. Nous identifions dix déterminants essentiels de la productivité, tous obtenus à partir de modèles théoriques différents. Notre spécification peut permettre de remédier au problème potentiel soulevé par l'omission de certaines variables. Les problèmes d'hétérogénéité entre pays et d'endogénéité sont également traités. La relation de détermination existant entre les sources de connaissances et la productivité semble robuste, mais d'autres déterminants retenus par différents modèles théoriques jouent également un rôle significatif. Les relations concernant la productivité sont hétérogènes entre les pays de l'OCDE, ce qui tend à indiquer que des facteurs nationaux spécifiques peuvent jouer un rôle important dans la politique relative à la productivité intérieure.

Classification JEL : F12; F2; O3; O4; C15

Mots clés : sources de connaissances, hétérogénéité dynamique, productivité multifactorielle (PMF), méthodes de moments.

SOURCES OF KNOWLEDGE AND PRODUCTIVITY: HOW ROBUST IS THE RELATIONSHIP?

1.   Introduction

Innovation is at the heart of growth models. In both class of models – exogenous and endogenous growth models – innovations drive long-run productivity and economic growth.[1] Given the central role of R&D, a voluminous empirical literature has examined the relationship between R&D and productivity. Micro studies, which typically focus on the manufacturing sector and analyse firm- and industry-level cross-sectional data (Mansfield, 1988; Griliches and Mairesse, 1990; Hall and Mairesse, 1995; Wang and Tsai, 2003; to name but a few) report statistically significant R&D elasticities of about 0.10 to 0.20 (Griliches, 1988). Studies that take a cost function approach (Nadiri, 1980; Nadiri and Purcha, 1990) also report positive and statistically significant returns to R&D. A strand of empirical studies focuses on the role of different sources of R&D.[2] Three distinct types of R&D – business sector, public sector and foreign R&D – are analysed and, in general, they are reported to have significantly positive effects on domestic productivity and/or on the reduction of production costs (*e.g.* Cohen and Levinthal, 1989; Geroski, 1995; Nadiri and Mamuneas, 1994; and Guellec and Van Pottelsberghe, 2004). Macro studies examine the role of R&D using aggregate data. They are either multi-country cross-sectional or panel studies (Lichtenberg, 1992; Coe and Helpman, 1995; Park, 1995; Keller, 1998). Time series studies are extremely scarce (Luintel and Khan, 2004). These studies also report: *i)* a significant positive effect of domestic R&D on domestic productivity and *ii)* positive and significant international knowledge spillovers. In view of the accumulating evidence, a consensus in the literature is that R&D contributes to domestic productivity and that knowledge spillovers are positive.[3]

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1 .   Exogenous growth models (*e.g.* Solow, 1956) treat technological progress exogenously whereas endogenous growth models (*e.g.* Romer, 1990a; Grossman and Helpman, 1991; Aghion and Howitts, 1992) endogenize innovations.

2 .   It is argued that public sector R&D focuses on "pure basic research" to advance the knowledge frontier whereas business sector R&D may lay equal emphasis on "applied research" and "experimental development". Product development is crucial for the profitability of business entities. The effect of foreign R&D on domestic productivity may crucially depend on the technological congruency and absorptive capacity of the country concerned (Griffith *et al*. 2004c). Thus, different sources of R&D may have different impacts on productivity.

3 .   Although in a minority, nevertheless there are few exceptions to this consensus. Panel studies on firm- and industry-level data (Griliches and Lictchenberg, 1984; Jaffe, 1986; Bernstein, 1988; Verspagen, 1995) report that R&D elasticities are often statistically insignificant. Likewise, on the sources of R&D, Poole and Bernard (1992) report a significantly negative effect of military innovations on the multifactor productivity of Canada.

2.   Motivation

Studies of R&D and productivity have focussed on the effects of knowledge and its sources on productivity, but have ignored two important issues of *i)* omitted relevant variables, and *ii)* cross-country heterogeneity.[4] These omissions could prove important *i)* if national productivity levels appear sensitive to factors other than knowledge stocks and *ii)* if the cross-country productivity levels exhibit different degrees of sensitivity to their determinants. On either issue, the answer is likely to be affirmative. This is because R&D is not the only driver of productivity – competing theoretical models of productivity abound – and there exist important cross-country differences in productivity levels, their growth rates and the fundamentals that drive them. Further, the efficacy of some of the productivity determinants may not be generalised. For example, 'learning-by-doing' may augment the productivity of a technological laggard but the same may not hold true for a technological leader. Similar arguments may apply vis-à-vis the technology 'outsourcing' which requires an appropriate domestic infrastructure base and the capacity to absorb foreign technology. This paper addresses both issues – omitted relevant variables and the cross-country heterogeneity – and re-examines the productivity relationship in a sample of 16 OECD countries. It applies a new approach to model cross-country heterogeneity. Consequently, it reveals the robustness of the effects of different sources of knowledge on productivity and sheds new light on the degree of cross-country heterogeneity in productivity relationships. The main arguments and contributions of this paper are as follows.

First, in addition to R&D, economic theory postulates a range of other determinants of productivity, viz., human capital, public infrastructure, access to export markets (learning-by-doing), imports, foreign direct investments (FDI), etc. However, to date, empirical studies have only gone as far as augmenting the productivity and R&D relationship by stocks of human capital; no study has examined the robustness of the sources of knowledge vis-à-vis other determinants of productivity that emerge from economic theory. This exclusion of relevant variables makes the empirical model mis-specified; consequently, parameter estimates become biased and the statistical inference becomes unreliable. In this paper, we estimate an empirical model of domestic productivity which, in addition to the three forms – domestic business (S^b) and public (S^p) sector and foreign (S^f) – of knowledge stocks, incorporates measures of human capital, physical infrastructure, access to export and import markets, inward and outward FDI, and a variable that captures the effects of business cycle. Thus, utilising the competing theoretical models of productivity as our guide, we evaluate the robustness of the sources of knowledge and identify the main drivers of domestic productivity for a sample of 16 OECD countries.

Second, the existing empirical literature mostly estimates fixed effects models, which do capture the country-specific fixed and the country-invariant time effects but imply that the parameters of productivity relationships are homogeneous across the sample countries. We call them 'homogeneous panel models'.[5] OECD countries differ markedly in their business and public knowledge stocks, human capital bases and infrastructure. R&D expenditures in business and public sectors also differ greatly. The scales of inward and outward FDI are different and so are the magnitudes of high tech exports and imports. They exhibit important cross-country differences in the growth rates of domestic productivity. In view of these differences, the assumption of homogeneous productivity relationships across OECD countries, as implied by the 'homogeneous panel models', appears quite strong and it is unlikely to hold. Instead, productivity

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4.   The stock of knowledge is typically measured based on either the flow of R&D expenditures in real terms or the patent counts. Following much of the literature on the subject analysed here, this paper takes the first approach, hence we use R&D and knowledge stocks interchangeably.

5.   Dummy variables are routinely used to capture some regional and/or country specific differences but our argument of heterogeneity is much more insightful and goes beyond the ability of dummy variables (see below).

relationships across OECD countries may show country-specific partial elasticities vis-à-vis their determinants. A rigorous scrutiny of this issue is important because: *i)* if parameters of productivity relationships are indeed heterogeneous across countries then their revelation may help design country-specific productivity policies better, and *ii)* if one ignores parameter heterogeneity in panel regressions when it is present then this invites yet another problem – it generates biased and inconsistent estimates.[6] Our second aim is precisely to model this cross-country heterogeneity in productivity relationships across the sample countries.

Third, we argue that cross-country differences in R&D intensity may not adequately capture the cross-country variations in domestic productivity levels. We suggest alternative measures and utilise them to model the cross-country heterogeneity in domestic productivity. Finally, we implement a state-of-the-art econometric approach – well established in growth empirics – which addresses the key estimation issues of endogeneity, weak instruments and measurement errors. The system GMM (Generalised Method of Moments) is our preferred estimator; nevertheless, we adopt a structured empirical strategy. We begin by reporting the customary static and first order autoregressive [AR(1)] 'homogeneous panel models' that employ OLS (Ordinary Least Squares) and IV (Instrumental Variables) estimators. These models are akin to those in the existing empirical literature which ignore cross-country heterogeneity. We then move on to a dynamic heterogeneous panel model – which accounts for cross-country heterogeneity in parameters – and to GMM estimators. This empirical approach reveals the robustness of our results vis-à-vis different specifications and estimators; and it allows us to compare our results with those in the literature.

A preview of our main results is in order. The parameters of productivity relationship are indeed heterogeneous across the sample OECD countries. Country-specific stocks of business, public and foreign knowledge exert significantly positive effects on domestic productivity; however, the magnitudes of these effects are different across countries. Besides the knowledge stocks, other determinants such as human capital, infrastructure, FDI, high tech exports and imports also exert significant country-specific effects on productivity. These latter effects are beyond those of the three sources of R&D.

We find that the higher the levels of S^b the greater tend to be the magnitude of international knowledge spillovers and the productivity gains from high tech imports. This is consistent with the view that knowledge spillovers require absorptive capacity, probably in the form of sizeable business sector R&D. Interestingly, however, a higher level of S^b tends to lessen the productivity effect of S^p. Results also reveal that S^b and S^p are not complementary vis-à-vis their productivity effects. A high S^p reduces the productivity effect of S^b and *vice versa*. However, S^p tends to complement the productivity effect of public infrastructure. A rather intriguing result is that the productivity effect of S^p is positively related to its size – there appears no diminishing return in the productivity effect of S^p. The higher the human capital base the greater tends to be the productivity of a country; but a higher human capital base tends to lessen the productivity benefits associated with inward FDI. Finally, a high stock of public infrastructure appears to augment the productivity effects of business sector R&D and high tech exports, but it lessens the productivity effect of high tech imports. Interestingly, the higher the level of infrastructure, the smaller its productivity effects tend to be – evidence of a diminishing return in infrastructure investment.

The rest of the paper is organised as follows. We discuss data in section 3; issues of heterogeneity in section 4; specification and econometric issues in section 5; empirical results in section 6; and section 7 summarises and concludes.

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6.   Here we are referring to the bias and inconsistency due to the neglected cross-country heterogeneity in productivity relationships. This may compound the problems of omitted variables.

3.   Data

We analyse 16 OECD countries (see Table 1). For the purpose of this paper, we collect data on multifactor productivity (P^m), domestic business (S^b) and public (S^p) sector knowledge stocks, foreign knowledge stock (S^f), stock of human capital (H) and public infrastructure related physical capital (Z), stocks of inward (F^I) and outward (F^O) foreign direct investments, ratios of high tech exports to total exports (X^h) and high tech imports to total imports (M^h), and a control variable for business cycle (U). Data frequency is annual for a period of 23 years (1980-2002). We have a balanced panel of 368 observations.

Data for P^m is obtained from the OECD productivity database. Data on S^b and S^p for each sample country is constructed from the flow of real R&D expenditures incurred respectively by the business and public (higher education and government) sectors. We use the perpetual inventory method to construct the stock measures (see Coe and Helpman 1995, among others). The relevant S^f for each sample country is computed as the weighted sum of the rest of the sample countries' S^b. We use bilateral time-varying weights: they are ratios of joint patent applications made by two countries at the European Patent Office (EPO) to their respective total patent applications at the EPO. Thus, we compute 15X23 matrixes of bilateral patent application ratios (R&D co-operation coefficients) for each sample country. To control for the sharp yearly fluctuations, we use three-year moving averages of both the numerator and the denominator while computing these weights.[7] The average years of schooling of age group 25 to 64 proxies the stock of human capital, data are obtained from Bassanini and Scarpetta (2002). We proxy the stock of public infrastructure by the stock of public physical capital stock constructed from government's gross fixed capital formation following the perpetual inventory method. Government's gross fixed investment data exclude expenditures on public R&D and military (military spending that can be used for civilian purposes is included in the government gross fixed investment data, however. For further details see, Ahmad *et al*., 2003).[8] The relevant series to compute X^h and M^h are obtained from OECD's STAN Indicators database. The control variable for the business cycle is computed as 1 minus the unemployment rate (see, Guellec and Van Pottelsberghe, 2004); data are obtained from OECD's ADB data base. Data on F^I and F^O are obtained from OECD and UNCTAD. Further details of all data series, their sources and computations are given in the appendix.

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7 .   This measure of S^f reflects the extent of successful R&D collaboration between nations leading to patent applications at the EPO. It also reflects the view that knowledge spills over between countries through R&D collaboration.

8.   We acknowledge that this is a crude measure of public infrastructure. No data exists on governments' aggregate stock of physical infrastructure. Studies use measures such as road mileage, telephone lines, supply of electricity, number of airport terminals etc. However, such indicators of public infrastructure appear more suitable for developing countries but, for obvious reasons, they are not appropriate for this analysis. Our sample of OECD countries may not show any significant changes in these measures of infrastructures during the late 20th and the early 21st century, which is essentially our sample period. Hence, we use governments' physical capital stock to proxy public infrastructure.

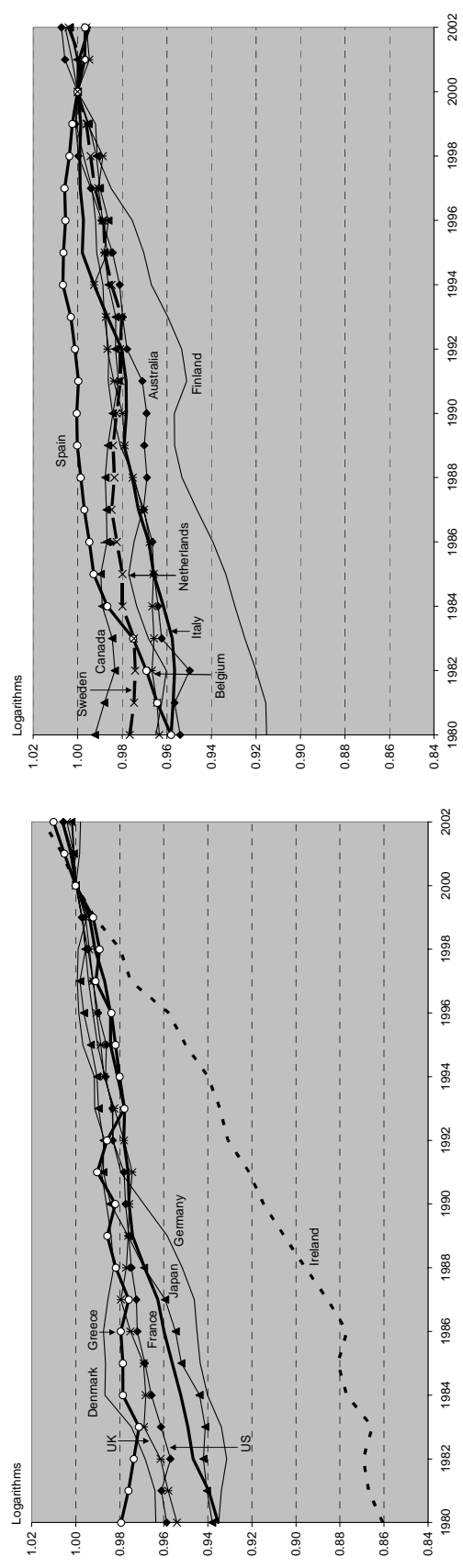**Figure 1: Multi-factor Productivity (2000=1)**

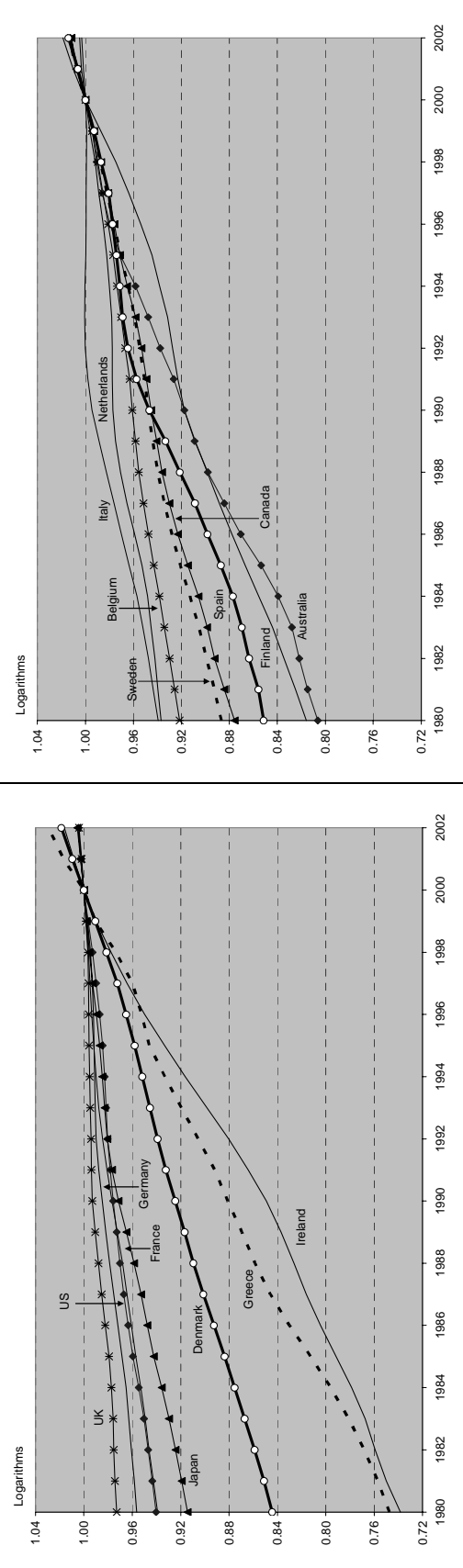**Figure 2: Business-sector R&D Capital Stocks (2000=1)**

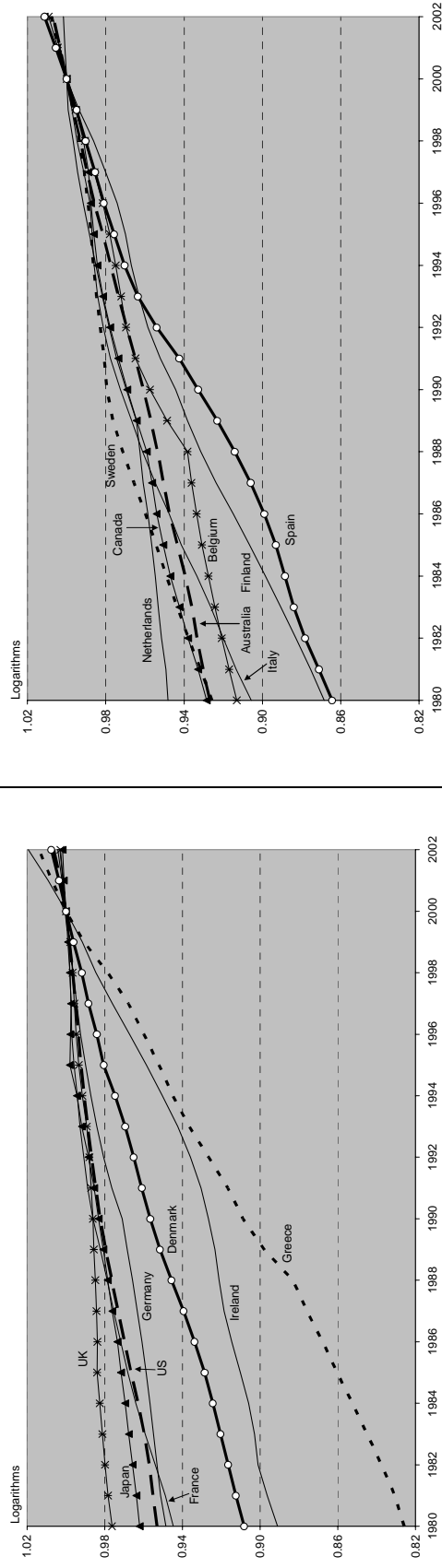## Figure 3: Public-sector R&D Capital Stocks (2000=1)

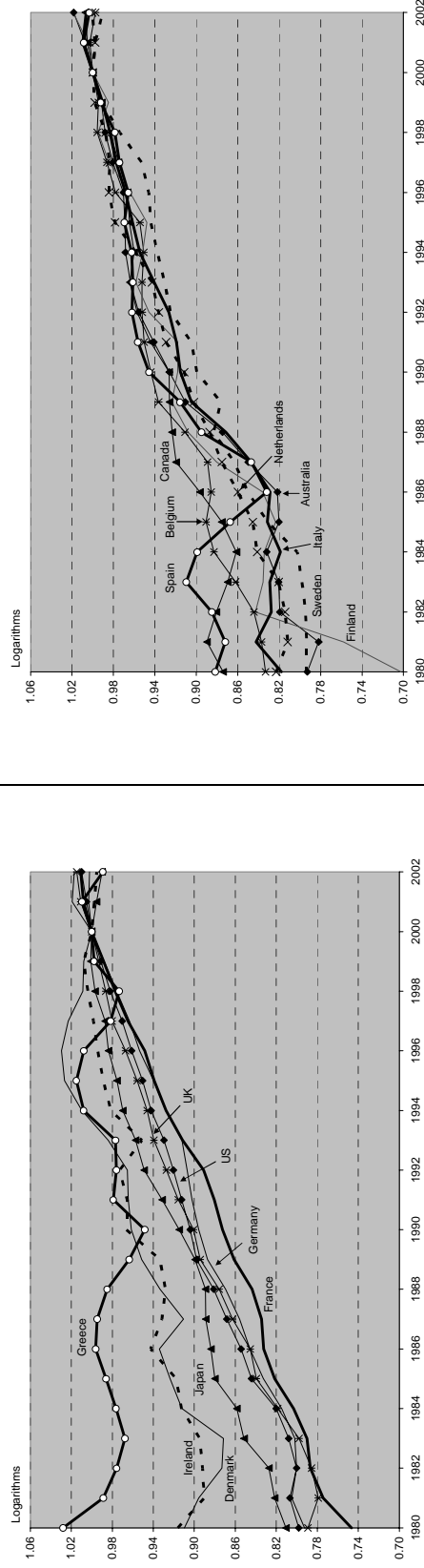## Figure 4: Foreign R&D Capital Stocks (2000=1)

Figure 1 plots data on P^m. All plots are normalised at 2000=1 for ease of cross-country comparisons. In econometric analyses, we use un-indexed data.[9] US productivity shows a modest upward trend throughout the sample period. UK productivity slows down during 1987-1991 but it improves somewhat since 1992. German productivity shows a noticeable rise throughout the 1980s but it stagnates from the early 1990s. Plots for Canada, Greece, Denmark and the Netherlands appear flat throughout. Australian productivity shows long swings – nevertheless the trend is clearly positive since the 1990s. French productivity was on the rise until 1990 but declined thereafter. Spanish productivity shows a strong positive trend in the early 1980s; stagnates during 1985-1995; and is in decline since 1997. Irish productivity shows a rapid rate of growth from its low base. The Finnish productivity trend appears similar to the Irish but the Finnish rate of growth is slower. Belgian and Italian productivity exhibit similar patterns of slow growth. Japanese productivity grew quite rapidly throughout the 1980s then appears quite similar to the other major industrialised countries since 1990. Finally, despite a high R&D intensity, Swedish productivity does not appear noticeably different from that of other countries in the sample. Overall, the plots indicate a general productivity slowdown in the 1990s compared to the 1980s.

Figure 2 plots S^b. They appear smooth and positively trended for most countries. The only two exceptions are Italy and the Netherlands whose plots of S^b appear rather flat since 1990. Plots of S^b also indicate cross-country variations in accumulation rates: Australia, Denmark, Ireland and Greece have accumulated S^b rapidly whereas mature economies like the United Kingdom, the United States, Germany and France have accumulated it relatively slowly. Other countries appear in-between.

Figure 3 plots S^p. They are also smooth and positively trended across all the sample countries. However, plots of S^p appear much flatter than those of S^b for the United Kingdom, Ireland and Japan whereas the opposite holds for Greece, Spain and Finland. Overall, S^p appears somewhat flatter in the late 1990s and into the 21st century than it was in the 1980s, which may reflect a gradual slowing down of public R&D expenditure.

Figure 4 plots S^f. Greece, Finland, Ireland and Spain show rather volatile foreign R&D stocks. This may reflect fluctuations in their weights rather than fluctuations in the domestic R&D stocks of other sample countries. For the rest of the countries, plots of S^f are on an upward trend. In view of the weights used, this indicates increasing bilateral R&D collaborations between the sample countries.

4.   Heterogeneity

Table 1 presents some summary statistics of our dataset. They show significant heterogeneity in the growth rates of productivity and their determinants across the sample OECD countries. The average annual growth rate of P^m ranges between a minimum of 0.2% (Canada) to a maximum of 3.3% (Ireland); the sample mean is 1.1%. The productivity of the United States and the United Kingdom grew by around 1% during the sample period; however, Japan, Germany and France experienced somewhat higher growth rates of 1.4% or above. The sample mean of business sector R&D intensity (business sector R&D expenditure to GDP ratio) is 1.6% but it ranges between a minimum of 0.1% (Greece) to a maximum of 2.2% (Sweden). Likewise, the intensity of public sector R&D ranges between a minimum of 0.3% (Greece) to a maximum of 0.9% (the Netherlands); the sample mean is 0.7%. Thus, business sector and public sector R&D intensity differ respectively by a factor of 22 and 3 across the sample countries. The stock of human capital appears lowest in Spain (7.6 average years of schooling) and highest in the United States and Germany

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9.   Lichtenberg and van Pottelsberghe (1998) illustrate the problems associated with the use of indexed data in econometric analyses.

(12.8 average years of schooling in each). The United States, the richest country in knowledge stocks and at the forefront of innovations, shares the smallest stock of S^f. Canada, Greece and Ireland appear to share large stocks of S^f. The intensity of public infrastructure (government's infrastructure related gross fixed capital formation to GDP ratio) ranges between a minimum of 1.74% (the United Kingdom) to a maximum of 7.35% (Japan). The cross-country intensity of high tech exports and imports differs respectively by a factor of 11.0 [from Greece (3%) to Ireland (33.5%)] and 2.2 [from Greece (9.8%) to Australia (20.6%)]. Likewise, the intensity of inward FDI (inflows of FDI to gross fixed capital formation) ranges between 0.3% (Japan) and 28.4 % (Ireland). The intensity of outward FDI ranges between a minimum of 0.4% (Greece) to a maximum of 18.4% (the Netherlands and Belgium).

Since all potential determinants of productivity – S^b, S^p, S^f, H, Z, F^I, F^O, X^h and M^h – differ across the sample countries, intuitively they can all be considered when modelling cross-country heterogeneity in productivity parameters. However, we assume that diversity in only four key variables – S^b, S^P, H and Z that together shape the domestic knowledge absorptive capacity of each country – adequately captures the cross-country heterogeneity in productivity parameters. Our focus on four key variables also circumvents the over parameterisation of the empirical model.

A close look at Table 1 suggests that several countries in the sample have comparable (in some cases identical) intensity measures, yet they exhibit enormous diversity in their stocks of knowledge and in other determinants of productivity. This is due to the acutely dissimilar size of OECD economies. For example, the United States and Japan have the same business sector R&D intensity of 1.9% but the United States' S^b is more than 2.5 times that of Japan. As a result, the US per capita S^b (*i.e.* S^b per head of labour force) is 1.4 times that of Japan. Denmark and the Netherlands have very similar business sector R&D intensity yet the Netherlands' S^b is almost three times that of Denmark. Consequently, the Dutch labour force enjoys 27% higher S^b per head compared to their Danish counterparts. Finland and France have identical (1.4%) business sector R&D intensities but the French S^b is much larger (eleven times) than Finnish S^b. French per capita S^b is 46% higher than Finnish per capita S^b.

Likewise, the intensity of public sector R&D also falls short of capturing the vast differences in S^p across the sample countries. For example, the United Kingdom and Germany have the same (0.7%) public sector R&D intensity but the German S^P is much larger than that of the United Kingdom; consequently, the German labour force enjoys a 14% higher public knowledge stock per capita than their UK counterparts. Australia, France, Finland and Japan show identical public R&D intensity of 0.8% but their stocks of S^P and per capita S^P vary notably. French per capita S^P is 48% higher than that of Finland; 32% higher than that of Australia; and 35% higher than that of Japan. A similar picture emerges vis-à-vis the public infrastructure but the extent is somewhat less than in the cases of S^b and S^P. It appears that the intensity measures can only reflect the cross-country diversity between a few disparate nations – *e.g.* between countries like Greece or Spain versus the United States or Germany. They reveal little for several of the major sample countries – for example, intensity measures reveal little between the United States versus Germany and/or between Denmark versus the Netherlands even though these countries differ substantially in their stocks of knowledge and public infrastructure. Thus, intensity measures appear rather unsuitable for capturing the cross-country heterogeneity in productivity parameters. This leaves us with two choices: country-specific mean levels of $S^b_{i,t}$ ($\overline{S}^b_i$), $S^p_{i,t}$ ($\overline{S}^P_i$), $Z_{i,t}$ ($\overline{Z}_i$), and $H_{i,t}$ ($\overline{H}_i$) or their respective per capita (per head of labour) measures. We utilise the country-specific mean levels to capture the cross-country heterogeneity in productivity parameters. The robustness of our results is also assessed by using per capita measures of $S^b_{i,t}$, $S^p_{i,t}$ and $Z_{i,t}$.

5.   Specification and econometric methods

We model domestic multifactor productivity in a sample of 16 OECD countries. We focus on three issues: *i)* robustness of the sources of knowledge vis-à-vis the omitted variables in affecting productivity, *ii)* cross-country heterogeneity in productivity relationships, and *iii)* endogeneity. We specify a general dynamic heterogeneous panel model for domestic multifactor productivity, which includes the major determinants of productivity postulated by economic theory and, at the same time, allows for cross-country parameter heterogeneity. We begin this by specifying a typical fixed-effect dynamic (autoregressive) equation for P^m that is common in the literature:

$$P_{i,t}^m = \alpha_i + \gamma_t + \lambda P_{i,t-1}^m + \beta_1 S_{i,t-1}^b + \beta_2 S_{i,t-1}^p + \beta_3 S_{i,t-1}^f + \beta_4 Z_{i,t-1}$$
$$+ \beta_5 H_{i,t-1} + \beta_6 X_{i,t-1}^h + \beta_7 M_{i,t-1}^h + \beta_8 F_{i,t-1}^0 + \beta_9 F_{i,t-1}^I + \beta_{10} \Delta U_t + e_{i,t} \tag{1}$$

(i= 1,…,N; t=1,…,τ_i; and $\Sigma \tau_i = T$) .

where "i" and "t" indicate the cross-sectional and time series dimensions; α_i captures the time-invariant fixed effects (*e.g.* differences in the initial productivity levels across countries) and γ_t captures the individual-invariant time effects (*i.e.* productivity shocks that are common to all countries). In equation (1) the dependent variable ($P_{i,t}^m$) is multifactor productivity; $S_{i,t-1}^b$, $S_{i,t-1}^p$ and $S_{i,t-1}^f$ denote the three sources of knowledge viz., the lagged business sector, public sector and foreign knowledge stocks. The lagged stock of public infrastructure is denoted by $Z_{i,t-1}$; $H_{i,t-1}$ stands for the lagged stock of human capital; $X_{i,t-1}^h$ and $M_{i,t-1}^h$ denote the lagged proportion of high tech exports and imports in total exports and imports, respectively; $F_{i,t-1}^0$ and $F_{i,t-1}^I$ stand for the stocks of outward and inward foreign direct investment (FDI), both lagged; and ΔU_t captures the effects of the business cycle on productivity.[10]

A brief discussion of the theoretical literature that motivates specification (1) is in order. All three sources of knowledge are expected to exert positive effects on multifactor productivity (see among others, Lichtenberg, 1993; Coe and Helpman, 1995; Keller, 1998; Nadiri and Mamuneas, 1994; Guellec and Van Pottelsberghe, 2004, to name but a few). Thus, the theoretical *priors* are that β_1, β_2 and β_3 resume positive signs and appear statistically significant.[11]

Customarily, measures of infrastructure directly enter as factors of production in private sector production function (Arrow and Kurz, 1970; Grossman and Lucas, 1974). In these models, the 'quality' and the 'size' of the public infrastructure augment productivity and growth through cost reductions and/or improved specialisations (see Gramlich, 1994 for a review). Aschauer (1989) attributes the 1970s US productivity slowdown to under-investment in infrastructure. A voluminous empirical literature has accumulated since but the evidence is far from conclusive. Aschauer (1990), Munnell (1990), Berndt and Hansson (1992), Nadiri and Mamuneas (1994), among others, report positive effects of infrastructure on productivity and economic growth; whereas Tatom (1991), Holtz-Eakin (1994), Gracia-Mila and McGuire (1992), Evans and Karras (1994) find it has a negligible or even negative role. Most of these empirical

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10.   For simplicity, only first order lags are shown in equation (1). In the estimation, we allow up to second order lags.

11.   One exception is Luintel and Khan (2004) who argue and show that knowledge spillovers (β_3) may not be positive for the technology leader.

studies are on industry level and/or micro data. Despite this empirical irregularity, we expect a positive effect of infrastructure on productivity on theoretical grounds; hence $\beta_4 \succ 0$.

The positive role of human capital in augmenting productivity and economic growth is embedded in both the exogenous and endogenous growth models (see, among others, Lucas, 1988 and 1993; Mankiw *et al.*, 1992; Romer, 1990a, b; Benhabib and Spiegel, 1994; Engelbrecht, 1997; Glomm and Ravikumar, 1992; Barro and Sala-i-Martin, 2003; Bassanini and Scarpetta, 2002); hence we expect $\beta_5 \succ 0$.[12]

The notion that export market access improves domestic productivity is the basis of the theory of 'learning-by-exporting' (Bernard and Jensen, 1999; Clerides *et al.*, 1998; Eaton and Kortum, 2001 and 2002). In these models, domestic firms improve their specialisation and productivity in the process of meeting the high product quality imposed by the foreign customers. In order to capture this 'learning-by-exporting' effect, we use a ratio of high tech exports to total exports and expect $\beta_6 \succ 0$.[13]

Imports are conduits of technology diffusion (Grossman and Helpman, 1991; Coe and Helpman, 1995; Keller, 1998 and 2004; van Pottelsberghe and Lichtenberg, 2001). Countries engaged in imports benefit from international knowledge spillovers. In particular, technological laggards are seen to benefit more than technological leaders. Recent literature on this issue emphasises the importance of trade in differentiated capital goods. We use a ratio of high tech imports to total imports to capture this effect and expect $\beta_7 \succ 0$.

FDI has two facets – foreign firms invest in domestic economy (inward FDI), and domestic firms invest abroad (outward FDI). Either form of FDI is conceived to foster technology diffusion and augment competition (see among others, Lipsey, 2002). Theoretically, FDI produces technological externalities and elevates the degree of product market competition, both of which boost productivity and growth. Hence, we expect β_8 and β_9 to be positive, *a priori*. However, the empirical evidence is not clear-cut. For example, Xu (2000), Keller and Yeaple (2003), Griffith *et al.*, (2004a, b) report positive and large FDI effects whereas Aitken and Harrison (1999) and Blonigen and Slaughter (2001), among others, find either negligible or even negative effects of FDI on productivity. Finally, ΔU_t represents the annual change in the rate of employment, which proxies for the business cycle effect on domestic productivity. Much of the literature predicts a pro-cyclical effect of the business cycle on productivity; hence, we expect $\beta_{10} \succ 0$.

Specification (1) is the standard fixed-effect model, which we called 'homogeneous panel model'. However, one difference from the existing literature is that specification (1) augments the basic productivity-knowledge relationship by most of the determinants of productivity postulated by economic theory. Although, specification (1) captures the unobservable fixed effects, it assumes homogeneous parameters and adjustment dynamics across all the sample countries in the panel. We have argued above that this assumption may be problematic in view of the heterogeneity in productivity levels (or growth rates) and its determinants across the sample countries. In this context, the best empirical strategy would be to conduct country-by-country econometric analyses of equation (1). Unfortunately, we only have 23 data points for each country and as is evident from equation (1) there are 10 theoretical determinants of

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12. Lucas (1993) and Romer (1990b) illustrate the different forms of human capital *e.g.* human capital acquired through schooling, learning-by-doing and engaging in trade.

13. We use the ratio of high tech exports to total exports assuming that it captures the quality aspect of exports better – *i.e.* improving quality (productivity) through exporting. In order to export high tech goods the exporting country needs to be technologically efficient and hence more productive. Likewise, a ratio of high tech imports to total imports is used to capture the productivity effect emanating from imports.

domestic productivity excluding the lagged dependent variable. This precludes us from conducting country-by-country time series analyses. We circumvent this by specifying a dynamic heterogeneous panel model that explicitly allows for the cross-country heterogeneity in productivity parameters. Our specification nests the 'homogeneous panel model' of productivity as a special case. Our specification is:[14]

$$P_{i,t}^m = \alpha_i + \gamma_t + \lambda_1 P_{i,t-1}^m + \lambda_2 (\bar{S}_i^b * P_{i,t-1}^m) + \lambda_3 (\bar{S}_i^p * P_{i,t-1}^m) + \lambda_4 (\bar{H}_i * P_{i,t-1}^m) + \lambda_5 (\bar{Z}_i * P_{i,t-1}^m) + \beta_k' W_{k,i,t}$$
$$+ \delta_k' (\bar{S}_i^b * W_{k,i,t}) + \theta_k' (\bar{S}_i^p * W_{k,i,t}) + \varphi_k' (\bar{H}_i * W_{k,i,t}) + \phi_k' (\bar{Z}_i * W_{k,i,t}) + \psi \Delta U_{i,t} + e_{i,t} \qquad (2)$$

where $W_{k,i,t} = [S_{i,t-1}^b, S_{i,t-1}^p, H_{i,t-1}, S_{i,t-1}^f, Z_{i,t-1}, X_{i,t-1}^h, M_{i,t-1}^h, F_{i,t-1}^o, F_{i,t-1}^l]'$; $\bar{V}_i = T_i^{-1} \sum_{t=1}^{T_i} V_{i,t}$;

$V_{i,t} \in (S_{i,t}^b, S_{i,t}^p, H_{i,t}, Z_{i,t})$; and (k = 1,...,9).

Specification (2) allows for the country-specific slope parameters ($\beta_k + \Omega$) – where $\Omega \in (\delta_k, \theta_k, \varphi_k, \phi_k)$ – and adjustment dynamics (λ_j) of productivity for each country in the panel. Country-specific parameters are assumed to depend linearly on the country-specific mean stocks of $S_{i,t}^b (\bar{S}_i^b)$, $S_{i,t}^p (\bar{S}_i^p)$, $Z_{i,t} (\bar{Z}_i)$, and $H_{i,t} (\bar{H}_i)$.[15] Thus, our specification states that the cross-country productivity parameters differ because countries differ in their levels of $\bar{S}_i^b$, $\bar{S}_i^p$, $\bar{Z}_i$, and $\bar{H}_i$.

In equation (2) if $\lambda_j = \delta_k' = \theta_k' = \varphi_k' = \phi_k' = 0$ holds for j=(1,..,5); then the relationship is static with homogeneous slope parameters. If $\lambda_j = 0 \cup \delta_k' = \theta_k' = \varphi_k' = \phi_k' \neq 0$ for j=2,..,5; then the relationship is heterogeneous in slope parameters but homogeneous in adjustment dynamics; if however $\lambda_j \neq 0 \cup \delta_k' = \theta_k' = \varphi_k' = \phi_k' \neq 0$, then the relationship is heterogeneous in both slope parameters and adjustment dynamics. From (2) the country-specific parameter vector (ϑ_i) can be obtained by:

$$\vartheta_i = \zeta_1 + (\zeta_2 * \bar{S}_i^b) + (\zeta_3 * \bar{S}_i^p) + (\zeta_4 * \bar{H}) + (\zeta_5 * \bar{Z}_i) \qquad (3)$$

where $\zeta_\ell = [\lambda_j, \beta_k, \delta_k, \theta_k, \varphi_k, \phi_k]'$; ($\ell = 1, 2,..,5$). The standard errors of country-specific parameters, $\sigma(\vartheta_i)$, are given by:

$$\sigma(\vartheta_i) = [\bar{U}_i' \Sigma \bar{U}_i]^{0.5} \qquad (4)$$

where $\bar{U}_{i,t} = (1, \bar{S}_{i,t}^b, \bar{S}_{i,t}^p, \bar{H}_{i,t}, \bar{Z}_{i,t})$ and Σ is the variance co-variance matrix of ζ_ℓ.

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14.   For the theoretical development of this modelling strategy, see Pesaran *et al.*, (2000).

15.   Pesaran *et al.,* find that when cross-country heterogeneity is accounted in this manner, the non-linearity in macroeconomic relationships disappears. In other words, the econometric evidence of non-linearity in macroeconomic relationships may be due to the neglected heterogeneity.

Econometric Issues

Any prospective estimator of equation (2) must address the issues of *i)* potential endogeneity – because productivity and some of its determinants may be jointly determined; *ii)* inertia – which may cause bias and imprecision in the estimated parameters; and *iii)* possible measurement errors. Amongst the available panel estimators, the system GMM estimator (Arellano and Bover, 1995; and Blundell and Bond (1998) appears best suited to tackle these estimation issues. For a brief illustration of GMM, we rewrite equation (2) by suppressing the interaction terms for simplicity as:

$$y_{i,t} = \alpha_i + \gamma_t + \lambda y_{i,t-1} + W_{k,i,t}\beta_k' + v_{i,t} \qquad (5)$$

where y_{it} denotes $P_{i,t}^m$; $W_{k,i,t}$ and β_k' are as defined above. If $E(v_{it}v_{is}) = 0$ holds for s≠t across all "i", then the following moment conditions are valid:

$E(y_{i,t-s}\,\Delta v_{it})=0$ for s≥2; t= 3,…, T. (6)

Furthermore, if a subset of W_{it}, say Q_{it}, is weakly exogenous then the following additional moment conditions also hold:

$E(Q_{i,t-s}\,\Delta v_{i,t})=0$ for s≥2; t= 3,…, T. (7)

The single equation (or the difference) GMM estimator utilises the above moment conditions. This allows the use of lagged (two periods or more) levels of endogenous and weakly exogenous model variables as instruments (see Holtz-Eakin, Newey and Rosen, 1988; and Arellano and Bond, 1991).[16] Thus, the GMM estimator uses internally generated instruments and it provides consistent parameter estimates.

However, when data are persistent – which is a common occurrence in macroeconomic series – and the time-series dimension is moderately short, the single equation GMM estimator suffers from the problem of weak instruments. In other words, internally generated instruments tend to be weakly correlated with the regressors. Consequently, the estimates suffer from large finite sample biases and poor precision (see, among others, Ahn and Schmidt, 1995 and Staiger and Stock, 1997). However, the system GMM estimator considerably reduces these biases and imprecision.

The system GMM estimator estimates a system of equations in the first differences and levels. It pools together (T-s) transformed (first difference) equations and an additional set of (T-s) level equations (note s ≥ 2). The first difference specification uses the suitably lagged levels of regressors as instruments whereas the level equations use the suitably lagged first differences. The latter are valid instruments if the following moment conditions hold:

$E[(\alpha_{i,t} + v_{i,t})\,\Delta y_{i,t-s}] = 0$ for s=1 (8)

$E[(\alpha_{i,t} + v_{i,t})\,\Delta W_{i,t-s}] = 0$ for s = 1 (9)

The consistency of GMM estimators requires a valid set of instruments and a non-auto-correlated residual series. The validity of the instruments in single equation and system GMM is tested respectively

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16. The first difference specification purges data of the fixed effects. However, there are other equally valid transformations – *e.g.* mean and/or orthogonal deviations – (see Arellano and Bond, 1991). We use mean deviations in equation (2).

by Sargan's instruments validity test and the Difference-Sargan test. We test for residual serial correlation through a second-order LM (Lagrange Multiplier) test.

6.   Empirical results

As a precursor, we report the results obtained from the fixed-effect static and the first-order-autoregressive panel models in Table 2. Although these are not our preferred specifications – because they do not capture the cross-country heterogeneity – nevertheless, we report them in order to compare our results with those in the literature. We report results pertaining to both the OLS and IV estimators.

The static fixed effects OLS estimates (column 2) show that S^b, S^f, H and M^h augment productivity in sample countries – their coefficients are positive and statistically significant at 10% or better. The coefficient of S^p is negative but insignificant. Thus, public sector knowledge stocks do not to appear to augment productivity. Likewise, X^h, F^I and F^O also appear statistically insignificant. The stock of public infrastructure appears negatively signed and significant. The ΔU_t resumes a positive and statistically significant coefficient, which is consistent with the expected pro-cyclical effect of business cycle on productivity. The fixed and time effects both appear significant, suggesting that the country- and time-specific shocks differ significantly across the sample countries. The point estimates obtained from the IV estimator (column 3) are qualitatively similar to those of OLS except that S^f and ΔU_t now turn statistically insignificant. Thus, fewer determinants of productivity appear statistically significant under the IV estimator. However, these static models suffer from the problem of residual serial correlation – the second order residual serial correlation tests are significant.

In column 4, we report the OLS based results of the first-order autoregressive model. Although the problem of residual serial correlation disappears, the results remain disappointing. The lagged dependent variable appears highly significant which flushes out the residual serial correlations but only two regressors (S^b and X^h) appear positive and statistically significant. S^p resumes a negative and statistically significant coefficient implying that the stock of public knowledge worsens productivity. The stock of infrastructure is also negatively signed but insignificant. Inward FDI is negative and significant whereas outward FDI appears negative but insignificant. ΔU_t is positive but insignificant. The IV results (column 5) appear even more disappointing; besides the lagged dependent variable, only one determinant of productivity – S^b – remains positive and significant; S^p and ΔU_t appear negative and significant; all other determinants appear insignificant.

Overall, these results are uncomfortable because *i)* they are in disagreement with the existing empirical literature that reports positive and statistically significant effects of the sources of knowledge on domestic productivity, and *ii)* they appear inconsistent with different theoretical models of productivity because most theoretical determinants proposed appear insignificant. Nevertheless, they send an important message that the positive and statistically significant effect of the sources of knowledge reported by earlier fixed-effects models may not be robust once the other potential determinants of productivity are accounted in the empirical model. Indeed, when we estimate model (1) using only three sources of knowledge as regressors, the results appear broadly consistent with the literature – S^b and S^f appear positive and

significant whereas S^p appears insignificant.[17] Thus, the results of Table 2 cannot be ascribed to our (extended) data set alone. We put forward two potential explanations for reconciliation.

First, the existing empirical studies exclude several of the potential determinants of productivity (discussed above) from specification. Two well-known results in econometrics are that the omission of relevant variables results in *i)* biased parameter estimates, and *ii)* unreliable significance tests. Put simply, when the actual regression excludes the relevant variables, the standard errors of its parameters become unequivocally smaller than when it includes the relevant variables. Consequently, the parameters of a mis-specified short regression appear precisely estimated when in fact that may not be the case. This may explain why most regressors appear insignificant in our fully specified model [Specification (1)].[18]

Second, fixed effect models are only credible as long as the assumptions of cross-country homogeneity in parameters and adjustment dynamics hold. Ignoring parameter heterogeneity is another source of mis-specification, which also engenders bias and inconsistency in the estimates (Pesaran *et al.,* 2000). Thus, neglected heterogeneity may further compound the omitted variables problem. This raises doubts on the validity of previous panel results that merely focus on the sources of knowledge. Although, specification (1) includes most of the determinants of domestic productivity, it still leaves the cross-country heterogeneity unaddressed; therefore, the results of Table 2 are not without concern. Hence, the arguments of omitted variables and cross-country heterogeneity are worth pursuing. We now turn to our dynamic heterogeneous panel model (specification 2) and examine whether it sheds any new light.

Table 3 reports the results obtained from our dynamic heterogeneous panel model. Although our preferred estimator is the system GMM, we nevertheless report results based on three different estimators, namely, the dynamic heterogeneous OLS (DHOLS), the single-equation GMM, and the system GMM. To begin with, an interesting revelation is that results pertaining to all three estimators reject the homogeneity of slope coefficients. Two estimators – DHOLS and the system GMM – reject both the homogeneity of slope coefficients and adjustment dynamics across all the sample countries. Most level regressors remain insignificant but the mean interacted regressors appear statistically highly significant. Thus, allowing for cross-country parameter heterogeneity produces fundamentally different results. In sharp contrast to the results of fixed-effects models (Table 2), all but one – the exception being F^0 – theoretical determinants of productivity specified in equation (1) appear significant. It calls into question the validity of fixed-effects models that neglect cross-country heterogeneity while modelling productivity relationships. All estimated point elasticities of S^b, S^p, S^f, H, Z, F^I, X^h and M^h show significant cross-country variations which systematically depend on the mean levels of S^b, S^p, Z and H of the respective country.

The reported GMM results pertain to the first-step estimators. The P-values of parameter are computed using the robust standard errors. Our estimated models pass all relevant diagnostics. The second order residual serial correlation tests are insignificant, which ensures the consistency of GMM estimators. The Sargan and difference-Sargan tests confirm the validity of instruments used under both (single and system) GMM estimators. It is interesting to note that the time-invariant fixed effects (α_i) and individual-invariant time effects (γ_t) both continue to remain significant in spite of accounting for the cross-country parameter heterogeneity. This implies that the sample of OECD countries differs not only in their initial productivity levels (endowments) but they are also exposed to different productivity shocks.

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17.   When only three sources of knowledge are allowed in the regression (1), the estimated point elasticities are: 0.175 (0.095), -0.100 (0.391) and 0.049 (0.002), respectively, for S^b, S^p and S^f. Figures within parentheses are P-values.

18.   A formal derivation of these two well-known econometric results can be found, among others, in Greene (2003), pp. 149-151.

Our results reveal that the higher the stock of S^b, the bigger the international knowledge spillovers and the productivity gains from M^h tend to be. This is consistent with the view that knowledge spillovers require absorptive capacity, which may take the form of a sufficient accumulation of S^b. Results also reveal that higher stocks of S^b tend to lessen the productivity effects of S^p and *vice versa* implying that they are not complimentary in augmenting productivity. Surprisingly, higher stocks of S^b also appear to lessen the productivity effect of X^h, which is hard to explain.

We find two opposing effects of S^p; a high stock of S^p tends to lessen the productivity effect of S^b (yet again evidence of non-complimentarity) but it appears to complement the productivity effect of Z (public infrastructure). A rather intriguing result is that the productivity effect of S^p increases with its size – there is no evidence of diminishing returns on the productivity effect of S^p. In contrast, the larger the stock of public infrastructure the smaller tends to be its productivity effect. The higher the human capital base, the greater its effect on productivity tends to be – no evidence of diminishing returns in the productivity effects human capital either. However, a higher level of H seems to lessen the productivity effect of F^I. Finally, a higher level of Z appears to augment the productivity effects of S^b and X^h whereas it lessens the productivity effect of M^h. Technology outsourcing (F^O) appears statistically insignificant in explaining P^m and so does ΔU.

Table 4 reports the country-specific parameters based on the system GMM, computed as shown in equation (3), using the results of Table 3. Since the estimated country-specific parameters appear broadly similar across all three estimators, we focus on the parameters obtained from the system GMM as this estimator is superior to other estimators (see section V).[19]

The country-specific point estimates of $\partial P^m / \partial S^b$, $\partial P^m / \partial S^p$ and $\partial P^m / \partial S^f$ are positive and statistically significant for all sample countries except for one – S^p for Belgium appears positive but insignificant. Importantly, however, these parameters exhibit considerable cross-country heterogeneity. The point elasticity of $\partial P^m / \partial S^b$ range from a minimum of 0.015 (UK) to the maximum of 0.038 (Ireland); for $\partial P^m / \partial S^p$ they range from a minimum of 0.017 (Belgium) to the maximum of 0.049 (Australia). Likewise, the point elasticity of $\partial P^m / \partial S^f$ shows a difference more than twofold (compare the point elasticity for the United States and Greece). Thus, S^b, S^p and S^f exert positive and statistically significant effects of varying magnitudes on the productivity of sample countries. This is in sharp contrast to the results of 'homogeneous panel models' reported in Table 2. The point elasticities of S^b and S^p on domestic productivity appear very similar in their magnitudes; however, the coefficients of S^f appear smaller than those of S^b and S^p.

We find a positive and statistically significant effect of human capital on domestic productivity for eleven countries; insignificant for four countries (Belgium, Greece, Ireland and Italy); and negative and significant for Spain. The negative coefficient for Spain is puzzling and hard to explain. Again, the cross-country parameter heterogeneity is apparent. The eleven countries with positive and significant

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19. The country specific parameters are qualitatively similar across all three estimators except for the insignificance of F^I under the single equation GMM estimator. We do not report the country specific parameter associated with dynamic heterogeneous OLS and single-equation GMM estimators to conserve space. However, they are available on request.

partial elasticities ($\partial P^m / \partial H \succ 0$) show their magnitudes varying from 0.101 (France) to 0.269 (the United States). Germany, the United States, Canada and Australia show large effects of human capital on domestic productivity.

Five countries in the sample (Belgium, Finland, Greece, Ireland and Spain) show small negative but statistically significant effects of the stock of public physical infrastructure on their domestic productivity. For the remaining countries, the effect is statistically insignificant. Thus, government's infrastructure related physical capital stock does not appear to augment domestic factor productivity of any of the sample countries. This finding is consistent with some of the literature cited in Section 5 (*e.g.* Tatom, 1991; Holtz-Eakin, 1994; Evans and Karras, 1994).

The effect of inward FDI on domestic productivity is rather mixed. Of the 16 sample countries, 6 countries (France, Italy, Japan, Spain, the United Kingdom and the United States) show a positive and significant effect; 4 countries (Denmark, Finland, Greece and Ireland) show negative and significant effects; and for the rest (Australia, Belgium, Canada, Germany, the Netherlands and Sweden) the effect is statistically insignificant. The magnitudes of the estimated parameters are small; nevertheless, they differ across countries. Results indicate that countries with sizeable knowledge stocks and human capital bases may benefit from inward FDI in terms of their productivity enhancements. Interestingly, technology outsourcing – outward FDI – appears insignificant.

Six countries (Australia, Finland, Greece, Ireland, Italy and Spain) show positive and significant effect of high tech exports in their domestic productivity. However, for two major industrialised countries (the United Kingdom and the United States), its effects are negative and significant. The remaining eight countries show an insignificant effect of high tech exports on domestic productivity. Overall, it appears that the technologically advanced countries may not achieve productivity gains through learning-by-exporting; however, relatively less advanced OECD countries (*e.g.* Greece, Spain, Italy, etc.) may do so.

The partial semi-elasticity of M^h, ($\partial P^m / \partial M^h$), appears positive for two countries (Sweden and the United Kingdom); negative and significant for three countries (Ireland, Greece and Spain); and statistically insignificant for the rest. Although insignificant, the sign of the point estimates ($\partial P^m / \partial M^h$) appear positive for most of the industrialised countries. Interestingly, however, countries like Greece, Ireland and Spain appear to have an adverse impact of high tech imports on their productivity. Finally, the results also reveal a mild degree of cross-country variations in adjustment dynamics (λs).

Our results pass a number of robustness checks. As is evident from Table 3, results are robust to three estimators, viz., DHOLS, the single-equation and the system GMM estimators. The only exception is that F^I does not appear significant under the single-equation GMM estimator. We replaced the country-specific mean levels of S^b, S^p, H, Z by their per capita mean values to capture the cross-country heterogeneity. The results remain broadly similar. We also estimate the model by dropping, in turn, the United States, Germany, Greece and Spain from the panel. The reported results remain qualitatively the same.

7.   Conclusion and implications

Most empirical studies that investigate the role of knowledge on productivity concentrate on various measures of R&D as the sources of productivity. They rarely allow for the other determinants of productivity that emerge from theoretical models. In view of the competing theoretical models and the several potential determinants of productivity they propose – in addition to knowledge stocks we identify

seven other determinants in Section 3 – this sole focus on R&D may lead to omitted variable problems. If true, the estimated parameters become biased and their inferences unreliable. This raises concerns on these results. Further, existing empirical studies use autoregressive fixed effects models. While these methods are popular and allow for country-specific fixed and country-invariant time effects, they imply that productivity relationships are homogeneous across the sample of countries. In other words, they cannot address the potential cross-country heterogeneity in slope parameters and adjustment dynamics. Since countries differ in their levels of economic development and adjustment dynamics, one can contest this implied assumption of cross-country homogeneity in productivity relationships. Moreover, neglecting cross-country heterogeneity in parameters and adjustment dynamics in itself results in biased and inconsistent parameters – this may accentuate the problems of omitted variables.

This paper re-examines the knowledge-productivity relationship in a panel of 16 OECD countries by addressing both issues of *(i)* omitted variables and *(ii)* neglected heterogeneity. Our specification is probably the most comprehensive yet which incorporates, besides the three sources, knowledge stocks, measures of the stocks of human capital, public physical infrastructure, inward and outward foreign direct investments, and ratios of high tech exports and imports as well as a control variable for the business cycle. As outlined in section 5, these variables emanate from different theoretical models of productivity. Empirically, we specify a dynamic heterogeneous panel model – a new approach in dynamic panel modelling – that captures the cross-country heterogeneity in parameters and enables us to report country-specific parameters and their significance. The domestic productivity is proxied by OECD data on multifactor productivity.

An empirical analysis of this nature has both theoretical and practical relevance. At the theoretical level, revealing productivity determinants that pass empirical scrutiny may shed some light on the relevance of competing theoretical models. In practice, identification of the key drivers of productivity and their parameters may better inform policy making.

Our analyses provide some new and interesting insights. Estimations of our general model – specification (1) – following the fixed effects approaches using OLS and IV estimators, which are common in the literature, show almost all theoretical determinants of productivity being insignificant. Only the business-sector knowledge stock appears correctly signed and significant across these estimators. In contrast, results from our dynamic heterogeneous panel model – that allows cross-country heterogeneity in parameters and adjustment dynamics – show almost all theoretical determinants of productivity being highly significant. These results are robust to a range of estimators, viz., the OLS, the single equation GMM and the system GMM. This implies that the commonly applied static and the first order autoregressive fixed effect models reveal little because they are unable to capture the inherently heterogeneous productivity behaviour across the sample of countries. This finding may have implications that go deeper and beyond the modelling of productivity relationships in panel framework.

The results show that in addition to the sources of knowledge, several other determinants put forward by economic theory such as human capital, infrastructure, FDI, high tech exports and imports, exert significant country-specific effects on productivity. These effects are beyond those of the three measures of R&D. The magnitudes of productivity parameters differ across the sample countries and productivity relationships are essentially heterogeneous. The results also show that the higher the business sector knowledge stock the greater tends to be the magnitude of international knowledge spillovers and the productivity gains from high tech imports. It appears that the business and public sector knowledge stocks are not complementary but the latter tends to complement the productivity effect of public infrastructure. The higher the human capital base, the greater the productivity of a country tends to be. Public infrastructure investment shows diminishing returns vis-à-vis productivity.

All three sources of knowledge (S^b, S^p and S^f) exert significantly positive effects on domestic productivity. This effect is common across the sample countries with only one exception – S^p appears insignificant for Belgium. Human capital is another determinant of domestic productivity, which shows significantly positive effects for a majority of sample countries (11 out of the 16 countries). The insignificance of human capital for four countries and its negative sign for Spain are puzzling. The public infrastructure does not appear to augment domestic productivity – its effects are insignificant for 11 countries and significantly negative for the remaining five. Inward FDI and high tech exports show mixed results. High tech imports appear insignificant in most cases and technology outsourcing (outward FDI) does not appear significant.

According to our results, the sources of knowledge (S^b, S^p and S^f) and human capital (H) appear as the key drivers of productivity. Their parameters confirm to theoretical *priors* and they are statistically significant across all or for the big majority of sample countries. Therefore, these findings may be generalised. Other determinants – Z, F^I, X^h, M^h – show mixed results. They appear statistically significant in several cases but the signs of their parameters do not always confirm to theoretical *priors*. Thus, the latter set of productivity determinants are important at country level but their effects appear country specific and they may not be generalised. Given these insights, productivity policies across OECD countries may benefit if they account for country-specific factors.[20] Finally, why factors such as F^I, X^h and M^h exert opposing effects across countries – positive for some and negative for others – would be an interesting issue to explore in future research.

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20. It is important to note that statistically significant parameters carry important information. Even if their signs do not confirm to theoretical *priors*, a significant piece of information must receive due consideration in policy making hence the importance of these findings.

Table 1: Descriptive statistics (1980-2002 mean value)

	MFP[1]	Business R&D[2,3]		Public R&D[2,4]		Foreign R&D[2]	Human Capital[5]	Public Infrastructure[2,6]		High-technology[2,7]		Outward FDI[2,8]	Inward FDI[2,9]
	Growth rate	Expenditure [Intensity]	Stocks	Expenditure [Intensity]	Stocks	Stocks	Stocks	Expenditure	Stocks	Exports [Intensity]	Imports [Intensity]	Stocks [Intensity]	Stocks [Intensity]
AU	1.1	2.3 [0.6]	10.6	2.9 [0.8]	16.2	58.7	12.1	8.7	78.6	2.6 [4.4]	11.9 [20.6]	48.5 [6.3]	86.3 [7.9]
BE	0.7	2.7 [1.2]	14.8	1.0 [0.5]	5.6	92.2	10.1	4.9	94.8	13.3 [8.5]	14.8 [10.0]	66.9 [18.4]	88.1 [21.7]
CA	0.2	5.9 [0.9]	29.2	4.8 [0.7]	26.2	145.2	12.6	15.7	139.7	17.0 [8.5]	29.7 [16.7]	133.7 [10.9]	149.1 [5.6]
DK	0.7	1.3 [1.0]	6.1	0.8 [0.7]	4.5	48.9	11.1	2.2	30.4	4.5 [12.3]	4.3 [12.6]	18.4 [12.0]	18.5 [10.9]
FIN	1.9	1.5 [1.4]	6.9	0.8 [0.8]	4.3	26.2	10.6	3.5	38.6	4.2 [11.7]	4.1 [15.7]	15.9 [11.1]	8.2 [5.6]
FR	1.5	17.3 [1.4]	97.4	10.8 [0.8]	62.4	24.8	10.3	39.9	394.1	41.6 [16.5]	39.8 [15.4]	174.5 [9.9]	124.4 [6.0]
DE	1.4	28.4 [1.7]	165.3	12.3 [0.7]	70.9	18.7	12.8	37.7	490.3	62.1 [14.3]	60.4 [15.9]	213.1 [6.6]	165.6 [5.7]
EL	0.7	0.2 [0.1]	0.8	0.4 [0.3]	2.2	128.1	9.1	4.6	37.9	0.4 [3.0]	3.5 [9.8]	7.0 [0.4]	19.0 [1.0]
IRL	3.3	0.4 [0.7]	1.9	0.2 [0.4]	1.2	132.2	9.5	2.5	26.7	15.7 [33.5]	9.2 [26.4]	18.6 [3.0]	67.0 [28.4]
IT	0.8	7.2 [0.6]	41.5	6.1 [0.5]	32.5	17.3	8.6	36.9	382.4	21.8 [9.5]	30.2 [13.1]	96.5 [3.8]	70.0 [2.3]
JP	1.4	53.5 [1.9]	281.7	21.2 [0.8]	126.8	11.1	11.0	203.2	2229.4	77.9 [28.0]	29.3 [13.1]	191.6 [1.0]	19.5 [0.3]
NL	0.9	3.6 [1.1]	20.5	2.9 [0.9]	17.0	35.2	11.1	10.7	112.7	25.9 [16.1]	27.1 [17.9]	161.9 [18.4]	112.1 [18.4]
SP	0.8	2.5 [0.4]	12.2	2.3 [0.4]	11.3	50.4	7.6	22.9	176.2	7.4 [7.3]	17.7 [13.6]	61.7 [8.1]	96.0 [8.3]
SE	0.6	4.4 [2.2]	21.9	1.8 [0.9]	9.9	30.6	11.3	5.7	58.6	10.1 [16.5]	8.4 [16.4]	50.8 [16.0]	28.8 [13.4]
UK	1.1	16.1 [1.3]	98.5	7.9 [0.7]	48.7	57.7	11.3	17.8	179.0	57.1 [23.4]	56.8 [20.0]	380.5 [14.8]	235.3 [9.7]
US	1.0	138.5 [1.9]	759.3	45.7 [0.6]	260.7	7.3	12.8	236.6	2105.6	151.9 [29.2]	147.4 [18.9]	684.5 [4.3]	560.7 [4.0]
Mean	1.1	17.9 [1.6]	98.0	7.6 [0.7]	43.8	55.3	10.7	40.8	410.9	32.1 [15.2]	30.9 [16.0]	145.3 [5.7]	115.5 [4.8]

1. Multi-factor productivity. 2. Billions of constant 2000 PPP US dollars. 3. Intensity (business-sector R&D expenditure as a % of GDP). 4. Intensity (public-sector R&D expenditure as a % of GDP). 5. Stock of human capital is proxy by the average number of years of schooling of the population from 25 to 64 years of age. 6. Public infrastructure is proxied by the stock of public physical capital stock. 7. Intensity (high-technology exports (imports) as a % of total exports (imports)). 8. Intensity (outflow of foreign direct investment as a % of gross fixed capital formation). 9. Intensity (inflow of foreign direct investment as a % of gross fixed capital formation).

Country mnemonics: Australia (AU), Belgium (BE) Canada (CA), Denmark (DK), Finland (FIN), France (FR), Germany (DE), Greece (EL), Ireland (IRL), Italy (IT), Japan (JP), Netherlands (NL), Spain (SP), Sweden (SE), United Kingdom (UK) and United States (US).

Table 2: The fixed effects panel estimates				
	OLS static	IV static	OLS AR(1)	IV AR(1)
Constant	3.855 (0.000)	3.805 (0.000)	0.553 (0.000)	0.639(0.000)
$P^m_{i,t-1}$	-	-	0.917 (0.000)	0.893 (0.000)
$S^b_{i,t-1}$	0.105 (0.040)	0.100 (0.043)	0.019 (0.001)	0.022 (0.006)
$S^p_{i,t-1}$	-0.042 (0.534)	-0.043 (0.536)	-0.018 (0.036)	-0.028 (0.023)
$S^f_{i,t-2}$	0.024 (0.095)	0.022 (0.163)	0.001 (0.846)	-0.004 (0.268)
$Z_{i,t-1}$	-0.102 (0.016)	-0.099 (0.023)	-0.012 (0.113)	-0.011 (0.201)
$H_{i,t-1}$	0.378 (0.073)	0.399 (0.101)	0.021 (0.565)	0.049 (0.230)
$X^h_{i,t-1}$	0.264 (0.240)	0.244 (0.414)	0.117 (0.068)	0.123 (0.193)
$M^h_{i,t-1}$	0.832 (0.001)	0.981 (0.003)	-0.0001 (0.992)	0.058 (0.598)
$F^O_{i,t-1}$	-0.006 (0.760)	-0.002 (0.921)	-0.001 (0.620)	-0.001 (0.838)
$F^I_{i,t-1}$	-0.002 (0.916)	-0.005 (0.820)	-0.009 (0.002)	-0.006 (0.319)
ΔU_t	0.482 (0.027)	0.341 (0.542)	0.053 (0.656)	-0.577 (0.002)
α_i	(0.000)	(0.000)	(0.000)	(0.000)
γ_t	(0.000)	(0.000)	(0.000)	(0.000)
R^2	0.874	-	0.984	-
σ	0.037	0.037	0.014	0.015
AR [2]	(0.004)	(0.003)	(0.779)	(0.199)
Obs	333	332	333	332
AR [2] is the second order Lagrange Multiplier [LM] test of residual serial correlation under the null of no autocorrelation; α_i and γ_t are fixed and time effects, respectively. σ is the regression standard error. Numbers (.) are p-values. For IV estimates S^f is treated as weakly exogeneous. All other regressors, except for ΔU_t, are instrumented by their second order lags. ΔU_t is instrumented by ΔU_{t-1}.				

Table 3: Results of Dynamic Heterogeneous Panel model (Equation: 3)			
	OLS	**GMM single equation**	**GMM system**
$P_{i,t-1}^{m}$	1.324 (0.000)	0.826 (0.000)	1.116 (0.000)
$P_{i,t-1}^{m} * \overline{H}_i$	-0.216 (0.013)	-	-0.117 (0.080)
$S_{i,t-1}^{b} * \overline{S}_i^{p}$	-0.023 (0.001)	-0.029 (0.000)	-0.012 (0.071)
$S_{i,t-1}^{b} * \overline{Z}_i$	0.021 (0.000)	0.026 (0.000)	0.012 (0.033)
$S_{i,t-1}^{p}$	-	-0.195 (0.000)	-
$S_{i,t-1}^{p} * \overline{S}_i^{b}$	-	-0.028 (0.000)	-0.018 (0.004)
$S_{i,t-1}^{p} * \overline{S}_i^{p}$	0.005 (0.000)	0.052 (0.000)	0.022 (0.001)
$S_{i,t-1}^{f} * \overline{S}_i^{b}$	0.003 (0.001)	0.001 (0.060)	0.001 (0.115)
$S_{i,t-1}^{f} * \overline{H}_i$	-0.010 (0.002)	-	-
$H_{i,t-1}$	-1.799 (0.000)	-1.324 (0.000)	-1.704 (0.000)
$H_{i,t-1} * \overline{H}_i$	0.812 (0.000)	0.621 (0.000)	0.775 (0.000)
$Z_{i,t-1}$	0.191 (0.000)	-	-
$Z_{i,t-1} * \overline{S}_i^{p}$	0.035 (0.000)	0.023 (0.000)	0.023 (0.023)
$Z_{i,t-1} * \overline{Z}_i$	-0.046 (0.000)	-0.020 (0.000)	-0.019 (0.013)
$F_{i,t-1}^{I}$	-0.050 (0.000)	-	-
$F_{i,t-1}^{I} * \overline{S}_i^{b}$	-0.010 (0.000)	-	-
$F_{i,t-1}^{I} * \overline{S}_i^{p}$	0.016 (0.000)	-	0.006 (0.000)
$F_{i,t-1}^{I} * \overline{H}_i$	-	-	-0.024 (0.000)
$X_{i,t-1}^{h} * \overline{S}_i^{b}$	-0.197 (0.000)	-0.177 (0.000)	-0.215 (0.000)
$X_{i,t-1}^{h} * \overline{Z}_i$	0.175 (0.000)	0.156 (0.000)	0.188 (0.000)
$M_{i,t-1}^{h}$	-	0.541 (0.001)	0.460 (0.068)
$M_{i,t-1}^{h} * \overline{S}_i^{b}$	0.148 (0.000)	0.157 (0.001)	0.175 (0.000)
$M_{i,t-1}^{h} * \overline{Z}_i$	-0.126 (0.000)	-0.175 (0.000)	-0.184 (0.000)
ΔU_t	0.151 (0.159)	0.106 (0.303)	0.100 (0.377)
α_i	(0.000)	(0.000)	(0.000)
γ_t	(0.000)	(0.000)	(0.000)
σ	0.013	0.129	0.013
AR (2)	(0.149)	(0.244)	(0.321)
Sargan χ^2 [r]	-	226.2 [1135]	-
Diff. Sargan χ^2 [r]	-	-	53.9[115]
Observations	352	352	352

Note: Notes for Table 3 are as follows. AR(2) is the second order LM tests of residual serial correlation. Under GMM, these tests are on the first differenced residuals because of the transformation involved. α_i and γ_t are the fixed and time effects. Numbers (.) are p-values based on the robust standard errors. Sargan tests are χ^2 [r] distributed under the null of instrument validity. S^b, S^p, U, X^h, M^h and H are GMM-instrumented setting $S \geq 3$; S^f and the mean-interacted regressors are treated exogenously. Reported results remain robust even when S^f and the mean-interacted regressors are instrumented by their lagged values.

	λ	S^b	S^p	S^f	H	Z	F^I	X^h	M^h
AU	0.825 [a]	0.019 [a]	0.049 [a]	0.009 [a]	0.226 [a]	0.008	-0.002	0.007 [b]	-0.005
BE	0.846 [a]	0.034 [a]	0.017	0.010 [a]	0.085	-0.020 [b]	-0.004	0.008	0.003
CA	0.820 [a]	0.020 [a]	0.040 [a]	0.010 [b]	0.259 [a]	0.009	0.000	0.002	0.012
DK	0.834 [a]	0.023 [a]	0.030 [a]	0.009 [a]	0.162 [b]	-0.003	-0.007 [b]	0.011	0.009
FIN	0.840 [a]	0.027 [a]	0.026 [a]	0.009 [a]	0.121 [b]	-0.010 [c]	-0.007 [b]	0.014 [c]	0.006
FR	0.843 [a]	0.022 [a]	0.036 [a]	0.011 [b]	0.101 [c]	0.009	0.010 [b]	-0.007	0.015
DE	0.818 [a]	0.023 [a]	0.029 [b]	0.012 [a]	0.270 [a]	0.007	0.006	-0.016	0.024
EL	0.858 [a]	0.035 [a]	0.050 [a]	0.006 [b]	0.005	-0.026 [b]	-0.008 [b]	0.018 [a]	-0.034 [a]
IRL	0.853 [a]	0.038 [a]	0.024 [a]	0.007 [b]	0.040	-0.032 [b]	-0.012 [a]	0.121 [a]	-0.037 [b]
IT	0.865 [a]	0.030 [a]	0.037 [a]	0.011 [a]	-0.044	-0.006	0.011 [b]	0.012 [c]	-0.006
JP	0.836 [a]	0.034 [a]	0.033 [b]	0.012 [b]	0.153 [b]	-0.008	0.013 [b]	0.018	-0.006
NL	0.835 [a]	0.023 [a]	0.036 [a]	0.010 [a]	0.159 [b]	0.003	0.001	0.009	0.010
SP	0.879 [a]	0.033 [a]	0.036 [a]	0.009 [b]	-0.134 [b]	-0.015 [b]	0.007 [c]	0.018 [a]	-0.016 [a]
SE	0.833 [a]	0.022 [a]	0.023 [b]	0.010 [a]	0.173 [a]	0.003	-0.003	-0.012	0.029 [c]
UK	0.832 [a]	0.015 [c]	0.031 [b]	0.011 [b]	0.175 [a]	0.019	0.007 [c]	-0.046 [b]	0.050 [b]
US	0.818 [a]	0.025 [a]	0.031 [b]	0.014 [a]	0.269 [a]	0.010	0.014 [b]	-0.050 [c]	0.029
Mean	0.840	0.027	0.033	0.010	0.126	-0.003	0.002	0.007	0.005
SD	0.017	0.007	0.009	0.002	0.115	0.014	0.008	0.037	0.023

Table 4: Country-specific parameters based on the estimations of Table 3

Panel A: GMM system estimation

λs are solutions for the country-specific coefficients of the lagged dependent variables. Impact elasticities of all regressors are listed in their respective columns. Impact elasticity should be divided by 1-λ for the long-run elasticity. For example, the long run point elasticity of S^b (*i.e.* $\partial P^m / \partial S^b$) is 0.137 for the US. Superscripts a, b, and c indicate significance at 1%, 5% and 10%, respectively. The variances of country specific parameters are calculated as shown in equation (4) in the text.

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DATA APPENDIX

The relevant data series used are as follows. Multi-factor productivity (P^m); research and development expenditures of business (E_b^{RD}), higher education (E_{he}^{RD}), and government (E_{gov}^{RD}) sectors; stock of human capital (H); high technology manufactures exports (X^h) and import (M^h); bilateral joint patent application (PAT_{cop}) at the European Patent Office (EPO); gross domestic product (Y); business-sector value added (Y_b); government's fixed capital formation excluding the public R&D expenditure (I_{gov}); total employment (L); business-sector employment (L_b); government expenditure (E_{gov}); unemployment rate (U); purchasing power parity exchange rate 2000 (PPP); gross domestic product deflator (Y^P); government investment deflator (I_{gov}^p); and stocks of inward (F^I) and outward (F^O) foreign direct investments.

Data on P^m is obtained from OECD's Productivity database (P^m data for Germany is available from 1991 onwards, therefore we extrapolated the pre-1991 data from the TFP series of Timmer, Ypma and Van Ark (2003)). The source for E_b^{RD}, E_{he}^{RD}, E_{gov}^{RD} and Y_b is OECD's R&D database. PAT_{cop} is authors' own computation using the EPO patent data obtained from OECD's Patent database. X^h and M^h are derived from OECD's STAN Indicators database. OECD's definition of high tech industries includes the following ISIC Rev. 3 industry: Aircraft and spacecraft; Pharmaceuticals; Office, accounting and computing machinery; Radio, TV and communications equipment; Medical, precision and optical instruments (OECD, 2005). Data on Y, I_{gov}, L, L_b, E_{gov}, U, PPP, I_{gov}^p and Y^P are obtained from OECD's ADB database. Series on F^I and F^O are obtained from OECD (*International Direct Investment Statistics Year Book*) and UNCTAD (World Investment Reports).

Following the literature (*e.g.* Coe and Helpman, 1995; Luintel and Khan, 2004), business sector R&D capital stock (S^b) is calculated from E_b^{RD} using the perpetual inventory method. The nominal E_b^{RD} is converted into constant 2000 PPP US dollars by using the GDP deflator and PPP exchange rate (2000=100). The initial business-sector R&D capital stock (S_0^b) is calculated as:

$$S_0^b = \frac{E_{b,0}^{RD}}{g + \delta} \qquad \text{(A1)}$$

where δ is the depreciation rate, assumed to be 15.0%, g is the average annual growth rate of E_b^{RD} over the sample, and $E_{b,0}^{RD}$ is the initial value of E_b^{RD} in the sample.

The total public sector R&D expenditure (E_p^{RD}) is the sum of higher education and government sectors R&D expenditure ($E_{he}^{RD} + E_{gov}^{RD}$). The public sector domestic R&D capital stock (S^p) is computed

following the method shown in equation (A1); E_p^{RD} is expressed in constant 2000 PPP US dollars. The foreign R&D capital stock (S^f) for each sample country is calculated as the weighted sum of the rest of the sample countries' S^b :

$$S_i^f = \sum_{j=1}^{N-1} w_{ij,t} S_{j,t}^b ; i \neq j \qquad \text{(A2)}$$

where t = 1, 2,……, T_i, and i, j = 1, 2,..,15. The bilateral time varying weight ($w_{ij,t}$) between country i and country j, are the ratios of joint patent applications made by two countries at the EPO to their respective total patent applications at the EPO. We use three-year moving averages of both the numerator and denominator to avoid sharp yearly fluctuations. Patent data refers to patent applications at the EPO. Thus, we compute 15X23 matrixes of bilateral patent co-operation coefficient for each sample country. The stock of human capital (H) is proxied by the average number of years of schooling of the population from 25 to 64 years of age. Bassanini and Scarpetta (2002) kindly provided data on H .

Stock of public infrastructure investment is proxied by the stock of public physical capital. This is computed from I_{gov} series using the perpetual inventory method as shown in equation (A1). The nominal I_{gov} is converted into constant 2000 PPP US dollars by using the government investment deflator and the 2000 PPP exchange rate. A depreciation rate of 8% (see Luintel and Khan, 1999 and 2004) and the sample-period average growth rate of real I_{gov} are used to generate the initial stock of public capital. We would have liked to cover more than 16 OECD countries, but data constraints on P^m proved prohibitive.