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TECHNOLOGICAL CAPITAL AND TECHNICAL PROGRESS IN THE G5 COUNTRIES

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We conduct an empirical application based on Coe and Helpman's (1995) seminal work, in order to measure the elasticity of technical progress with respect to R&D capital for the G5 countries between 1971 and 2003. For this purpose, a series for technological capital is built for the 1990-2003 period, and linked with Coe and Helpman's series for the 1971-1990 period. The technical progress of leading countries depends critically on the domestic R&D capital stock, in line with Coe and Helpman's (1995) and Coe, Helpman and Hofmaister's (2009) work. Nevertheless, there are some important differences. The estimations for the elasticity values appear to be higher and show larger differences between countries than in previous studies. Furthermore, the results give evidence in favour of Schumpeterian models, as TFP growth is positively related to the distance to the technological frontier represented by the US.

JEL classification codes: O33, O50, O47
Key words: technology, R&D spillovers, dynamic heterogeneity, catching-up

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I. Introduction

Technical progress -one of the most important sources of productivity growth- depends critically on research effort; see for example Griliches (1994) and Zachariadis (2003). As the empirical endogenous growth theory pointed out during the early 90s, technical progress is strongly influenced by R&D expenditures, where more R&D inputs should induce more technology growth. This idea was used to develop the so-called first generation of the R&D-based models (Romer, 1990; Grossman and Helpman, 1991; and Agnion and Howit, 1992). The challenge facing the theory to account for long-run co-movements in knowledge and R&D motivated the development of empirical applications. Coe and Helpman (1995), and Eaton and Kortum (1996) established different relationships between productivity and research across OECD countries. These papers inspired a large number of empirical studies to deep into the appropriate definition of foreign capital stock, determinants of knowledge and the best econometric techniques to estimate the process (see Keller 2004; Luintel and Khan 2004, Coe, Helpman 1995 and Hofmaister 2009, for example). The main idea is that economies undertake their own innovation and, at the same time, benefit from international diffusion of ideas or innovations.

In this context, the current work aims to estimate the elasticity of technical progress with respect to domestic and foreign technology inputs, in order to study the dynamics of knowledge heterogeneity across a sample of worldwide leading countries. The technology output is measured as the total factor productivity (TFP), while technology inputs are proxied by R&D capital stocks, which are, in turn, positively related to other inputs, such as number of researchers and patents. Our work takes its inspiration from Coe and Helpman's (1995) seminal study, although it offers a number of novel contributions. First, the time period is extended to include the 1990-2003 sub-period, updating the data set to cover the complete 1971-2003 period. These years, which actually match up with those in Coe, Helpman and Hofmaister (2009), have been considered as a period of intense integration in the markets for goods, services and capital internationally.

Second, the sample is limited to the five leading research economies, that is: the United States, Japan, Germany, France and the United Kingdom (G5, henceforth). The question that arises is the reason to restrict the study to this one sample of countries. We assume, based on an ample literature, that these countries represent the technology frontier, and are consequently able to extend it. In particular, Eaton and Kortum (1996, 1999), Jones (2002), Keller (2004) and Ha and Howitt (2007) found that the G5 countries are by far the main generators of spillovers worldwide.

Additionally, G5 European countries have shown a slower economic growth path than the US, specially since the 90s, that is related with a decrease in the research and development intensity -in comparative terms- and the coexistence of technological gaps among these countries (Perez and Esteve 2007; Myro et al. 2008).[1]

The purposes of this paper are threefold. The first is to compare the empirical results with those of previous studies, although the use of different functional specifications limit the comparison. The new results provide insights into the role of technological progress in these economies. The second aim of the paper is the estimation of TFP country-specific elasticities with respect to R&D inputs. In doing so, it is useful to test whether the estimated cross-country coefficients are significantly different across countries.

We also quantify the extent of the country specific innovations and diffusion by decomposing each country' technology variance into the contribution made by domestic and foreign efforts. The third goal of the paper is to test whether TFP is enhanced by the distance to the theoretical frontier in order to follow the predictions of the Schumpeterian theory.

The main findings are that the results from this paper confirm those of Coe and Helpman (1995), Luintel and Khan (2004) and Coe, Helpman and Hofmaister (2009), although a number of interesting differences emerge. In each of these works, technical progress of developed countries depends critically on the domestic R&D capital stock and to a lesser extent on the foreign R&D capital stock. However, the current results show a substantial increase in the mean and standard deviation among countries. The elasticity range of values helps us to establish a classification, where France and Germany are on the top of the rank while Japan is at the bottom. The estimations give some support to the Schumpeterian growth theory; so far, it corroborates the assumption that TFP growth is positively related to the distance to the frontier. However, it does not support that research intensity spillovers consistently influence TFP growth.

The remainder of this paper is divided as follows. Section II presents the theoretical framework and develops the model. Section III describes the variables and data used. Section IV presents evidence of the importance of R&D spillovers. Section V offers a sensitivity analysis where the estimation results are studied under different assumptions. Finally, Section VI offers some concluding remarks.

[1] Dimitz (2001) calculated that the TFP gap for Germany, Ireland, Italy and the United States was about 6% at the end of the 20th Century.

II. Theoretical framework and specification

This work uses Jones' (2002) production function, which explicitly includes human capital, and implicitly research intensity, to capture the concept of technological progress more precisely. Thus the economic environment is characterised by a finite number of economies, using a Cobb-Douglas production function:

$$Y_{it} = K_{it}^{\alpha} H_{Yit}^{1-\alpha} A_{it}^{\sigma}, \quad 0 < \alpha < 1, \sigma > 0, \tag{1}$$

where Y is the total output, K is the physical capital stock, H_Y is the quantity of human capital employed to produce goods, A accounts for the technical progress, α is the participation of the physical capital in the output, and σ is the elasticity of the product with respect to technical progress. Subscripts i and t account for country and time, respectively. Notice that aggregate human capital producing output is given by:

$$H_{Yt} = h_t L_{Yt}, \tag{2}$$

where h is human capital per worker and L_Y is the total amount of raw labour producing output. Because time spent in school is excluded from labour force data,

$$L_t = L_{At} + L_{YT}, \tag{3}$$

where L denotes employment and $l_Y = L_Y / L$ the proportion of total employment occupied in the production of goods. Therefore, the production function in equation (1) can be rewritten in terms of output per hour worked $y = Y/L$ as:

$$y_t = \left(\frac{K_t}{Y_t} \right)^{\frac{\alpha}{1-\alpha}} l_{Yt} h_t A_t^{\frac{\sigma}{1-\alpha}} . \tag{4}$$

We therefore assume $\sigma = (1-\alpha)$ and so A is measured in units of Harrod-neutral productivity. Empirically we can obtain the contribution of technology from equation (4) using the well-known Solow residual:

$$A_{it} = \frac{y_{it}}{\left(\frac{K_{it}}{Y_{it}} \right)^{\frac{\alpha}{1-\alpha}} l_{Yit} h_{it}} . \tag{5}$$

Human capital per worker can be expressed as $h_i=e^{\psi(Ei)}$, where E accounts for the worker's average years of education, and $\psi(\cdot)$ is a linear function which is expressed as follows: $\psi(E)=\psi E$. The slope explains the increase in income as a result of an additional year of education. The variable A accounts for technology and also it includes factors that influence the final output (assuming given amounts of physical capital, labour, education and research intensity).

Technical progress can depend positively on technology inputs. Several empirical papers have demonstrated that the TFP level is influenced by the R&D stock; and also that some of the major channels of technology diffusion across countries may involve international trade (i.e. Coe and Helpman 1995, Guellec and the la Poterie 2004, Keller 2004 and Coe, Helpman and Hofmaister 2009). Our specification assumes that technology is produced according to:

$$A_{it} = \beta_i \left(RD_{it}\right)^{\phi_d} \left(RF_{it}\right)^{\phi_f m_{it}} e^{\varepsilon_{it}}, \qquad (6)$$

where RD and RF are the domestic and foreign knowledge stock, respectively, m represents imports as a percentage of GDP, β is a parameter that measures heterogeneity among countries, which is supposed to be constant over time, and ε is an i.i.d. disturbance term. Finally, ϕ_d and ϕ_f represent the elasticity of TFP with respect to domestic and foreign capital, respectively. We can obtain the elasticity of total capital by adding domestic and foreign capital elasticity. Taking log in equation (6), it leads to:

$$a_{it} = \log\left(\beta_i\right) + \phi_d rd_{it} + \phi_f m_{it} rf_{it} + \varepsilon_{it}, \qquad (7)$$

where a, rd and mrf represent the logarithms of TFP, log(A), domestic R&D stock, log(RD), and import-share weighted foreign R&D stock, $m$log(RF). This expression is growing in its arguments and captures the two dimensions of technical progress. One source of such progress comes from the local technology system, which scope depends on R&D capital stocks and its capacities for invention and technical innovations. The other source considered is the technical spillovers as a function that depends on invention and innovations that can cross national borders. According to Grossman and Helpman (1991), the quality of intermediate goods imported from abroad increases the production efficiency of the host company. So, that modifies the extent to which foreign firms benefit from these spillovers and it depends on the economic relations between the countries. Therefore, the level of productivity achieved by a country is determined not only by its own research efforts but also by the capacity to access and import knowledge from abroad, resulting in an improvement in the performance of domestic and foreign firms (Griliches, 1998).

Equation (7) can be estimated under the null hypothesis that the regressors are orthogonal by construction. However, this hypothesis is probably not applicable in the current case, since the domestic and foreign R&D capital stocks could be correlated. Specifically it is not possible to identify what part of the variance of *a* is attributable to the variance of *rd*, and the variance of *mrf* using a growth accounting decomposition. To circumvent this problem, Klenow and Rodríguez-Clare (1997) proposed an informative way of characterizing the data, i.e. to split the covariance term in half to give *rd* and *mrf* the same weight, as follows:

$$\frac{\text{var}(a)}{\text{var}(a)}=\frac{\text{cov}(a,x)+\text{cov}(a,z)}{\text{var}(a)}=\frac{\text{cov}(a,x)}{\text{var}(a)}+\frac{\text{cov}(a,z)}{\text{var}(a)}=1, \tag{8}$$

where $x = (rd,mrf)$ and $z=(\varepsilon)$. If we regress *rd* and *mrf*, respectively, on *a* (after incorporating the country effect in the error term), then we will be able to obtain a good approximation of equation (5).[2] In turn, $\text{cov}(a,x)$ can be decomposed again into:

$$\text{cov}(a,x)=\phi_d^2\text{var}(\text{rd})+\phi_f^2\text{var}(mrf)+2\phi_d\phi_f\,\text{cov}(rd,mrf). \tag{9}$$

The approach in equation (7) assumes no catch-up term with respect to technological progress. However, this constraint is too restrictive for some countries (Parente and Prescott 2004; Benhabib and Spiegel 2005, among others). In Schumpeterian models (i.e., Aghion and Howitt 2006), a country at the technological frontier can make incremental improvement of existing leading edge technology, while countries that are inside the frontier can implement technologies developed elsewhere, thus allowing for international technology spillovers. Recent papers (i.e. Ha and Howitt, 2007 and Madsen, 2008) have provided empirical support to the Schumpeterian theory for the OECD countries over the past century. The growth in knowledge can be expressed by:

$$\Delta a_{it}=\gamma_{0i}+\gamma_1\Delta rd_{it}+\gamma_2\Delta mrf_{it}+\gamma_3\log\left(RD/Y\right)_{it}+\gamma_4\log\left(RF^m/Y\right)_{it} +\gamma_5\left(\frac{A_{ust-1}-A_{it-1}}{A_{ust-1}}\right)+\varepsilon_{it}\,. \tag{10}$$

[2] Considering *a=rd+mrf*, the OLS offers a linear operator where adding the coefficients will lead us to a proxy of Eq. (6). Note that if domestic and foreign capital are independent, then *cov(rd,mrf)*=0.

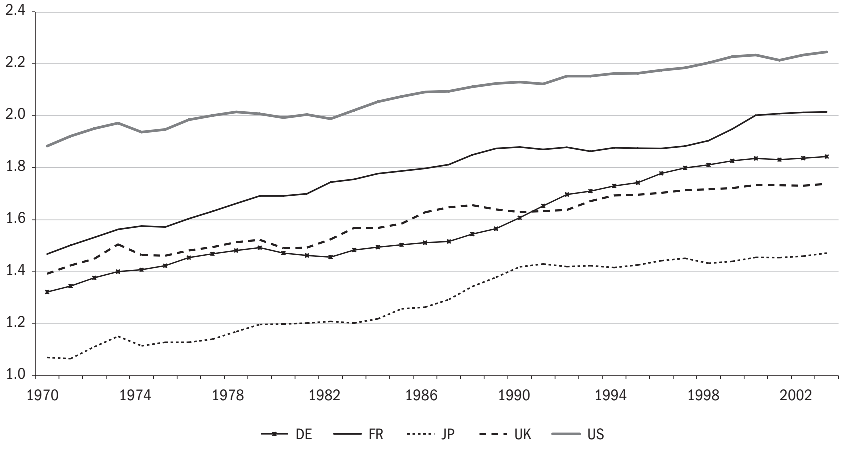
We can use this equation to examine two of the main assumptions of the Schumpeterian theory. Firstly, we can see if TFP growth depends on the distance to the technological frontier. In equation (10) it is captured by the last term, a catch up term representing the rate of technology diffusion from the United States to country i. The idea is that the further the i´s country is located from the leader country, the more it will benefit from reducing the technology gap. According to Griffith et al. (2003) the parameter γ_5 depends on the country's institutional idiosyncrasy. Secondly, we test whether TFP growth is consistently influenced by research intensity (we have used income as a proxy for the number of products). The dependent variable is the TFP growth rate and the explanatory variables enter in logarithmic terms.

III. Data

The variables TFP and R&D stock have been built using data from the business sector. All the variables are measured in constant 1995 US dollars adjusted for purchasing power parity. Details about the variables, as well as other relevant issues of their construction, and data sources are reported in the Appendix. The sample consists of the 5 leading OECD countries, viz., Germany, France, Japan, the United Kingdom and the United States. As in the Coe and Helpman (1995) and Coe, Helpman and Hofmaister (2009) studies the data for Germany refer to West Germany from 1971 to 1990 and for unified Germany thereafter. Data frequency is annual for a period of 33 years (1971-2003). Figures 1-4 plot the data series required for the core analysis.

We estimate the TFP series from equation (5) using Jones' (2002) approach. Then, we assume a value of 1/3 for the capital coefficient, α, following the recommendation of Mankiw (1995) and Gollin (2002). We have assigned a value of 7% for the parameter ψ, which corresponds to the return to schooling, as usually specified in the labour-market literature (Mincer, 1974). According to Figure 1 there are important differences in TFP levels among the countries. Furthermore, the plot shows an increasing trend in TFP over the 1971-2003 period, with growth rates ranging from 1% for the US and Japan to 1.6% for Germany and France. As a result these countries TFP have increased from 0.61 times the one in the US, in 1971, to 0.73 times in 2003. A dramatic stagnation occurred in Japan, since the economic collapse of the early nineties, which has been accompanied by a sharp break in its TFP series.

Figure 1. Total factor productivity, in logarithms



In order to calculate domestic capital stocks for the different economies between 1990 and 2003, we focus on Coe and Helpman's perpetual inventory procedure. The idea is to link our series to the ones that those authors constructed for the 1971-1990 period. The main objective consists in obtaining homogeneous series for the overall 1971-2003 period. The year 1990 acts as a pivot, being common to both sub-samples. Figure 2 shows that Japan has seen the biggest increase in domestic capital (7.1% annual growth rate), followed by Germany (4.7%), France and the US (3.5%), and finally the United Kingdom (1.4%).

In order to obtain the Foreign R&D capital stocks for our sample of countries, we have calculated the import-share weighted R&D stocks of their OECD trade partners. Figure 3 shows a slight increase in foreign R&D capital across countries. It is interesting to note that the US path presents the most upward trend, a 5.1% growth rate *versus* 3% for Germany and the United Kingdom, and 2.3% for France and Japan. Finally, Figure 4 plots the evolution of imports as a percentage of GDP. It has been multiplied by a factor of 2.6 in the US economy, compared to a factor of 1.6 for France and Germany, and 1.2 for Japan and the United Kingdom. These differences in the domestic and foreign capital stocks, as well as in the import rates across countries, can explain, at least partially, some of the empirical results obtained when estimating the elasticities of technical progress.

Figure 2. Domestic R&D capital stocks, in logarithms (1985=1)

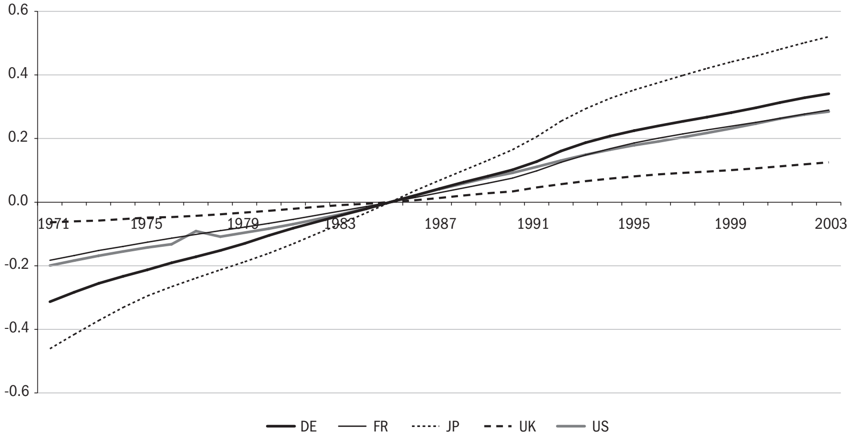


Figure 3. Trade weighted foreign R&D capital stocks, in logarithms (1985=1)

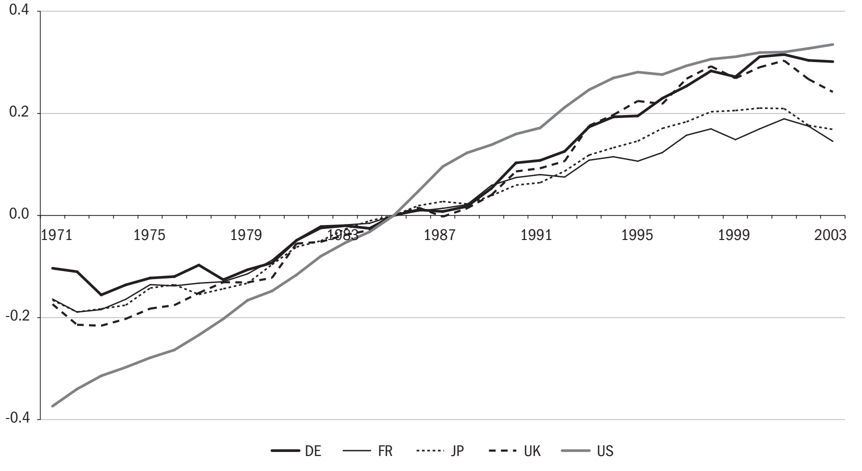


Figure 4. Import share

IV. Econometric methods and estimation results

If we observe the plots of data in Figures 1-4, we can confirm that the variables *a*, *rd* and *mrf* clearly trend upwards, not so the import share in Figure 4. We test for non-stationary random disturbances and correct for possible cointegration effects. Thus, we first implement the Augmented Dickey-Fuller (ADF) procedure, in which the null hypothesis is that the series are non-stationary. Regarding the trend underlying our data, the Schwartz criterion assumes a regression that has an intercept component and follows a linear trend. The results, along with critical values, are reported in Table 1. They do not provide sufficient evidence to reject the null hypothesis of I(1) at a highly significant level (1% or better), all series appearing to be unambiguously integrated of order 1, consistent with earlier findings (i.e., Coe and Helpman 1995, Luintel and Khan 2004 and Coe, Helpman and Hofmaister 2009).

Secondly, the estimation procedure tests for cointegration relationships by using Johansen's procedure. The results under specification (7) are reported in Table 2, and suggest that there exists a single cointegrating vector. This paper considers that the level data have no deterministic trend and the cointegrating equations have restricted intercepts. In addiction to the three stochastic variables, the system contains a constant. The null hypothesis of no co-integrating vector is rejected at the 1% level for the sample of countries. Thus variables are co-integrated in all cases and so equation (7) is estimated by using the dynamic ordinary least squares (henceforth, DOLS) estimator of Stock and Watson (1993), as the best one for cointegrated equations. The DOLS estimation include, as additional variables, one-period lags and leads and concurrent values of explanatory variables in first differences to capture the dynamic path around the long-run equilibrium. The advantage of DOLS over OLS is that it possesses an asymptotic normal distribution and yields unbiased coefficients in panels (Kao and Chiang 2000). Estimates from co-integrated panels show robustness to problems such as omitted variables, endogeneity or measurement error, etc.

One side of the analysis that is novel in this paper is the estimation of country-specific elasticities. Besides the upward trending variables, Figures 1-4 show significant divergences across countries that could give rise to heterogeneity of

Table 1. ADF unit root tests

	DE	FR	JP	UK	US
log(*A*)	-1.94	-2.28	-1.71	-3.29	-3.52
log(*RD*)	-1.38	-1.69	-1.28	-2.73	-3.18
*m*log(*RF*)	-2.44	-2.80	-3.30	-4.25	-3.20

Notes: The Augmented Dickey–Fuller regressions include an intercept and a linear trend. 1% (5%) critical value for ADF statistics equals -4.28 (-3.55).

Table 2. Johansen cointegration tests for log(*A*), log(*RD*), and *m*log(*RF*)

	Hypothesized no. of CE (s)	Eigenvalue	Trace statistic	1% critical value
DE	None***	0,64	49,39	41,20
	At most 1	0,31	17,30	25,08
FR	None***	0,52	41,17	41,20
	At most 1	0,32	21,26	25,08
JP	None***	0,54	46,80	41,20
	At most 1	0,46	22,96	25,08
UK	None***	0,54	47,89	41,20
	At most 1	0,46	23,73	25,08
US	None***	0,60	47,96	41,20
	At most 1	0,36	19,31	25,08

Notes: Trace test indicates 1 co-integrating equation at the 1 percent. The test assumes no trend in the series with a restricted intercept in the cointegration relation, and uses one lag in differences. *** (**) denotes rejection of the hypothesis at the 1% (5%) level.

R&D spillovers. To ensure whether pooling is valid it is useful to explicitly test from equation (7) whether the estimated cross-country coefficients for the two independent variables are significantly different across countries; and then to present results where the estimated coefficients on both domestic and foreign R&D capital are constrained to be the same across countries (Baltagi 2001). Therefore, formal tests for the heterogeneity of the TFP relationship are conducted. First, panel A of Table 3 reports standard (Chow type) F-tests under the null that country specific parameters are equal to the corresponding panel estimates; tests reject the null. Thus, the elasticity of TFP with respect to domestic and foreign R&D capital stocks across G5 countries is significantly different. This holds for the coefficient vector and for both R&D measures. Further, panel B presents the White's test statistic of error variances across countries, under the null of a common variance against the alternative of the group wise heteroscedasticity (Green, 2003). The test strongly rejects the null of homoscedasticity across countries; as a result, the data set can not be pooled. Moreover, the estimation rejects, at the 1% level, the null hypothesis that the individual effects are not correlated with other regressors (Baltagi 2001), indicating that the model to apply is the fixed-effects model.

Table 4 presents DOLS estimates on the R&D dynamics given by equation (7). All the equations include unreported country-specific effects. A number of important questions arise form the analysis of results. On the one hand, the interpretation of the effect of domestic R&D capital stock on TFP is straightforward; the coefficients exhibit the expected positive sign and are statistically highly significant. Germany and France bear the highest elasticity, followed by the US and Japan; the one for the United Kingdom is probably too high. On the other hand, however, the evidence

Table 3. Heterogeneity of R&D and TFP dynamics across countries

Panel A. Test for equality of:	*c, rd, mrf*	*rd, mrf*	*rd*	*mrf*
F-tests	313.09***	99.74***	68.34***	12.34***
F (n_1, n_2)	F(16,116)	F(12,120)	F(8,124)	F(8,124)
Critical Value (1%)	2.22	2.37	2.69	2.69
Panel B. Test for group homoscedasticity across countries				
White test	12.34***			
Degrees of freedom	2			
Critical value (1%)	9.21			

Notes: Panel A: Equality of *c*, *rd* and *mrf* are standard (Chow type) F-tests under the null of parameter equality across G5 countries. Panel B: Reports chi-squared statistics under the null hypothesis of a common variance against the alternative of the group-wise heteroscedasticity. *** (**) denotes rejection of the hypothesis at the 1% (5%) level.

Table 4. TFP parameters estimates of equation (7): log(*A*) is dependent variable

	DE	FR	JP	UK	US
log(*RD*)	0.43***	0.37***	0.17***	0.74***	0.32***
	(0.03)	(0.04)	(0.02)	(0.07)	(0.04)
*m*log(*RF*)	-0.05	0.08**	-0.13***	0.01	-0.02
	(0.03)	(0.03)	(0.03)	(0.04)	(0.04)
R^2 adjusted	0.92	0.94	0.97	0.93	0.98
Total elasticity	0.43	0.45	0.04	0.74	0.32

Notes: method is DOLS. All equations include unreported country specific constants. Hausman test (75.1) indicates that the most accurate model is the fixed-effects model at the 5%. White heteroscedasticity consistent standard errors and covariance in parentheses. *** (**) denotes statistical significance at the 1% (5%) level.

is not as robust with regard to the effect of foreign R&D capital on TFP. The coefficients for *mrf* are not significant and only France exhibits a positive elasticity.

In short, Table 4 reports significant parameter heterogeneity of R&D dynamics across the sample of countries. TFP depends critically on the domestic R&D capital stock, whereas weighted-import research is almost insignificant. International spillovers appear flowing to France, one of the less R&D-intensive nations, while Japan's wrong sign can be due to the collapse of the early nineties. We also find equivalent R&D spillovers across Germany and France, which may be the result of technological resemblance and geographical proximity, as pointed out by Keller (2002). He finds a strong geographically decay in his analysis of technology diffusion between countries. The next section offers some possible explanations for those findings.

V. Sensitivity analysis

Having analytically estimated the R&D spillovers across countries, we offer different implications of the results with respect to the different sources of technical progress and its variation. On the one hand, the estimations for the G5 countries are consistent with previous works (Coe and Helpman 1995, Luintel and Khan 2004 and Coe, Helpman and Hofmaister 2009, for mentioning only a few), although a number of differences are worth mentioning. The main differences are that, compared with those of Coe, Helpman and Hoffmaister (2009), the estimated coefficients on *rd* are larger while the coefficients on *mrf* are smaller or even insignificant. Instead, estimates from Table 4 are more prominently in agreement with Luintel and Khan (2004). Estimations clearly show the considerable cross-country heterogeneity in the estimated point elasticity of TFP with respect to domestic and foreign R&D

knowledge stock. These results give support to the hypothesis of domestic and international R&D spillovers are significantly different across countries, and that can not be pooled. However, the international spillover coefficient result is negative, -0.13, for Japan, thus generating a net spillover of 0.04. The elasticity of technical progress with respect to domestic R&D for the United Kingdom seems to be excessively large.

One of the possible sources of the discrepancies with Coe and Helpman (1995) and Coe, Helpman and Hoffmaister (2009) springs from the treatment of human capital. Several empirical papers, including Engelbrecht (1997), Benhabib and Spiegel (2005) and Coe, Helpman and Hofmaister (2009) have established that the level of TFP is influenced by the human capital stock in the OECD countries. Attributing a return of 7% for the private sector could lead to an underestimation of the human capital's contribution to the marginal product. Ashenfelter et al.'s (1999) finding establishes that the rates of return to schooling appear to be higher in the US than elsewhere, what gives support to our conclusion.

A second source of discrepancy could lie in differences about the temporal frequency of the data used. In this paper we use annual observations for the current estimations, while Coe and Helpman (1995) and Coe, Helpman and Hofmaister (2009) use five-year averages. Since the TFP and R&D growth seems to be predominantly pro-cyclical, the correlation between the variables may be driven by the business cycle and transitional dynamics, and not by a genuine structural relationship. As an alternative, we also have estimated equation (7) using four-year averages.[3] The results, which are not reported in the paper, suggest a positive relationship between TFP growth and domestic R&D growth for the US. On the other hand, for non-leading countries there are practically no differences between the alternative estimations and the previous ones using annual observations. Nonetheless, the coefficient assigned to capture the effect of the distance to the technological frontier appears to be positive and significant for all the countries.

A directly related question is whether technology diffusion within countries is larger than across countries. The literature generally supports this hypothesis. In order to test this hypothesis we compared the TFP elasticities for the domestic and foreign R&D –as discussed in Section IV–. However, it is now possible to undertake a growth accounting exercise. Most of the empirical counterparts of the variables in equation (7) are readily observed and the values for the parameters come from

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[3] We have not included five-year averages, as in previous studies, since it is advisable not to reduce the degrees of freedom excessively.

the estimations reported in Table 4. Thus, Table 5 presents the results for the decomposition of the covariance obtained from equations (8) and (9). Several remarks concerning this approach are relevant. First, the model explains around 95% of the TFP variance for the G5 countries. Second, we find that for Germany, the United Kingdom and the US nearly all the technology variance could be attributable to the long-run movements of domestic R&D capital; the share fall to about 82% in France and Japan. We close by stressing that the domestic R&D capital accounts for most of the TFP variance across the sample of countries.

The results that we have presented rely on a number of specific assumptions. We now examine the implications of changing one of the most controversial: does TFP among countries converge over time? Results of estimating the TFP growth model given by equation (10) are reported in Table 6, in this case the catch up term is restricted to zero for the US. The coefficients for both domestic and foreign innovative activity growth are predominantly insignificant. This suggests a non significant social return to investment in domestic R&D, since R&D expenditures are already included in capital and labour, and therefore in the estimates of TFP (Madsen, 2008). On the other hand, foreign research intensity is significant and it has the predicted sign for France, but neither for Germany nor Japan. Finally, the estimated coefficients related with the distance to the frontier are significant for all countries but Germany. This result is consistent with the theory provided by Schumpeterian models: TFP growth potential depends positively on the distance to the frontier, the larger the distance the higher the growth potential, converging toward the leading edge technology. These findings are also consistent with those of Eaton and Kortum (1996, 1999), Luintel and Khan (2004) and Madsen (2008).

Table 5. Decomposition of covariance of log(*A*)

	DE	FR	JP	UK	US
Regression variance	0.028	0.020	0.017	0.010	0.010
Total variance	0.027	0.022	0.018	0.010	0.010
% of explained variance	104	91	93	95	101
% of regression variance accounted for:					
- Domestic R&D	100	81	83	100	100
- Foreign R&D	0	19	17	0	0

Table 6. TFP parameter estimates of equation (10): Δlog(*A*) is dependent variable

	DE	FR	JP	UK	US
Δlog(*RD*)	-0.19	-0.17	-0.27***	0.02	0.02
	(0.27)	(0.18)	(0.09)	(0.04)	(0.07)
Δ*m*log(*RF*)	0.00	0.02	0.01	0.01	0.04
	(0.01)	(0.02)	(0.02)	(0.02)	(0.06)
log(*RD*/*Y*)	0,01	0.01	-0.04***	0.04	0.00
	(0.02)	(0.03)	(0.01)	(0.03)	(0.05)
log(RF^m/*Y*)	-0.02***	0.03***	-0.04***	-0.02	-0.09***
	(0.01)	(0.01)	(0.01)	(0.02)	(0.02)
DTF	0.01	0.23**	0.63***	0.48**	
	(0.07)	(0.10)	(0.13)	(0.24)	

Notes: Method is OLS. $DTF=(A_{US}-A_i)/A_{US}$. All the equations include unreported country specific constants. White heteroscedasticity consistent standard errors and covariance in parentheses. ***(**) denote statistical significance at the 1% (5%) level.

VI. Summary and conclusions

Coe and Helpman´s paper and the large literature inspired by it have provided evidence in support of positive and homogeneous R&D spillovers across countries. Furthermore, Coe, Helpman (1995) and Hofmaister (2009) have recently revisited their seminal work concluding that the new results confirm those reported in their previous work. However, the cointegration techniques applied do not allow for the possibility of heterogeneity across countries.

We agree with Luintel and Khan's (2004) argument, i.e., technology diffusion is likely to be heterogeneous, since countries differ in terms of technology stages and research intensities. We test whether the data can be pooled under the null of parameter homogeneity across G5 countries for the period 1971-2003. Our results reject the null hypothesis of the equality of panel and country-specific elasticities of TFP with respect to both domestic and foreign capital. The distribution of knowledge diffusion hardly appears to be uniform. Therefore, we estimate the elasticity of technical progress with respect to the R&D capital stocks at country level in order to study the dynamics of knowledge heterogeneity. Our findings corroborate some of the stylized empirical regularities and they also shed some light on the R&D spillovers dynamics performance. One of those stylized facts is that technical progress depends critically on the domestic R&D capital stock, and our estimates show this to be the case. We find that almost 90 percent of the differences in TFP can be attributable to differences in the stock of domestic capital among countries. Our work does not support, however, another stylized fact, i.e., that international R&D spillovers are positive and do not differ across OECD countries. Our estimates differ from those in Coe and Helpman (1995) and Coe, Helpman and Hofmaister (2009), first in the value of the coefficients associated with domestic R&D spillovers that, in our work, are larger than in Coe and Helpman (1995). Second, the coefficients for international R&D spillovers are significantly smaller and some of them even insignificant. In sum, knowledge diffusion is heterogeneous across countries and thus long-run spillover elasticities differ significantly among them, as in Luintel and Khan (2004). The variance decomposition process provides similar results.

Our results confirm that the US is, by far, the main generator of spillovers, but not a net receiver. This finding is consistent with the argument that knowledge spills over from the technology frontier -here represented by the US- to followers in the long-run. Moreover, significantly negative spillovers are found for Japan, probably because of declines in the price of equities and land since the collapse of the early nineties. Additionally, there is evidence that the importance of technology diffusion increases with economic integration and declines due to geographical distance; France and Germany represent a good example in this case.

Finally, it is clear that well-functioning markets are conducive for successfully technology invention and adoption. US firms may react more intensely to changes in the economic cycle than those of other countries, and a bi-directional relation may exist between growth of technical progress and R&D. The European economies have a greater weight of public initiative, and so R&D would seem not to be so directly linked to the performance obtained from it. These findings are worth investigating in future studies, which could also look more closely at the causes of the low elasticity with respect to foreign capital. While conventional wisdom is that learning-by-importing effects are non-existent, this matter requires addressing further research.

Appendix

Sources and construction of data:

- GDP per hour. The data for GDP at 1995's constant prices were calculated using Eurostat (Statistical appendix to European Economy).
- People in work. The starting point is the total employment in 1960, obtained from OECD Labour Force Statistics. The series for the following years was obtained by applying to that number the rates of variation provided by Eurostat, in European Economy.

- Working hours. Weekly working hours in non-agricultural activities were obtained from the Work Statistics Directories, published by the International Labour Organization (ILO), whilst it was necessary to use various issues of the OECD Labour Force Statistics in order to estimate some of the values for the United Kingdom.
- Human capital. The data for average years of educational training for population over 25 years old come from De la Fuente and Doménech (2006), Barro and Lee (2000) and OECD (2005).
- Engineers and scientists engaged in R&D activities. The source (National Science Board and OECD) is the same as in Jones (2002).
- R&D capital stock. OECD Main Science and Technology Indicators. The variables are measured in constant 1995 US dollars adjusted for purchasing power parity (World Bank Indicators).
- Import rates. Annual National Accounts for OECD Member Countries (2005).

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