Researchers, Distance to Frontier and Technology Growth

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Abstract:

This paper examines the effects on growth and productivity of the R&D activities using a version of Jones´ leader-follower growth model that allows different technological frontier of economies. We consider a change of scenario where the technological frontier transcends the world technological leader to undertake how technological improvements occur in different economies and if they mainly respond to imitation or innovation. The model is estimated using the Kalman's filter for economies close to the frontier, as the United States and some leading European countries. We find that European countries rely on innovations from the US for over 55% of its total growth. These findings are not robust to alternative definitions of the technological frontier. Thus, the hypothesis of a frontier that surpasses the US boosts the performance and the dispersion of the R&D workforce. The impact on American steady-state growth rate is significant, rising from 0.3 to 0.7%.

Keywords: productivity growth, innovation and Kalman's filter.

JEL codes: E17, O33, O47.

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1. Introduction

What began fifty years ago as a residual factor is now shaping up as the main source of growth in the most developed economies (Solow, 1957). Growth accounting shows that technological progress explains much of the increase in per capita income (Griliches, 1994). Nonetheless, as Eaton and Kortum (1996) pointed out, where it originates and how it spreads across countries is less well understood, owning to the difficulty of observing the creation or diffusion of inventions. The new theory of growth establishes that the efficiency at work could be understood as a combination of knowledge and technology, which make possible to justify differences in worker productivity. As a result, the recent development of the growth literature focuses on the disparities observed among countries in terms of access to knowledge, and its effects on economic growth and productivity. In this sense, the work of Jones (2002a, 2005) explains how the worldwide discovery of ideas occurs and Papageorgiou (2003) allows for technological imitation in addition to innovation in a restricted way. These studies were inspired by other seminal papers that inferred the extent of technology innovation on productivity growth (Nelson and Phelps, 1966; Romer, 1990; Rustichini and Schmitz, 1991; Caballero and Jaffe, 1993 and Coe and Helpman, 1995). The lately works that have quantified the importance of international technology diffusion, as the one by Bils and Klenow, 2000, Jones, 2002b and Massini *et al* (2005) emphasize the role of infrastructure as one of the main determinants of the productivity growth differences observed among countries.

Our paper belongs to this group of studies that try to explain the role of innovation and imitation in determining whether countries will attempt to adopt more productive technologies and whether researcher's productivity is the same or different across economies. Whereas, we examine how these determinants affect technology growth rate in a non-restricted model allowing for a technology frontier displacement.

As a starting point, we use a version of the Jones (2002) leader-follower growth model in order to examine the relation between technical progress and their determinants. In our version we consider different technological frontier economies, where researchers can choose between imitation activities, adopting the world frontier technologies, or they can work on innovation activities at the local technological frontier. At a point in time, a technological improvement results from a combination of both sources. We assume that in well-integrated markets the distribution of resources among imitation or innovation activities responds to the relative productivity criteria and that the researcher's productivity increases when the amount of ideas (the world knowledge) makes the technological frontier to expand. As a consequence, the distribution of research and development activities (R&D) in non-integrated markets could follow a non optimal pattern based on incentives other than the relative productivity allocation framework.

This version of the Jones´ growth model is tested empirically. We estimate the model with the aim to fit international patterns of technical progress presenting evidence by using a dataset from four countries close to the technological frontier between 1950 and 2001. The sample includes the US economy, considered the one placed at the frontier, and three European countries (France, Germany and the United Kingdom), all of them capable of inventing and re-creating technology. The critical test of our model is whether it is consistent with the observed technical progress disparity across countries, and we find it is.

Accordingly, the paper examines the effects on growth and productivity of the R&D activities considering a change of scenario where the technological frontier transcends the world technological leader. In order to undertake the new distribution pattern and discuss its effects, we need to start setting the situation in which the frontier lays on the more technological advanced economy, and compare it with another scenario where it surpasses the leader technological frontier. Thus, we can be concerned about how technological improvements occur in different economies and if they mainly respond to imitation (what we call trade of ideas) or innovation.

The rest of the paper is organized as follows. Section 2 lays out the basic structure of the innovation-diffusion model. Section 3 presents the empirical analysis, which includes a brief review of the data and the definition of variables. It also contains the estimation results based on the two different scenarios proposed: depending on whether the technological frontier coincides with the leader country or it expands. Section 4 presents the main implications and Section 5 concludes.

2. Theoretical Framework

In this section, we first outline the economic environment. The economy produces a final good by using intermediate capital goods. An approach to a discrete time version of the Cobb-Douglas production function, based on Romer (1990), yields:

$$Y_{t+1} = L_{Yt}^{1-\alpha} \sum_{j=1}^{A} x_{jt}^{\ \alpha} \ , \tag{1}$$

where Y is output produced in time $t+1$, L_Y is the portion of labour employed in the output sector in t, x_j is the amount of intermediate good j used in final production, again in t, A is a domestic technological index expressing the capital goods the workers can use, and $\alpha \in (0,1)$ is the share of intermediate x_j in output.. The economy consists of identical infinitely lived agents, and population grows exogenously at rate $n>0$. The agents can be engaged in the production of the final good or in the R&D sector that produces intermediate capital goods. There are no aggregate increasing returns to scale in this economy.

Romer (1990) considers that economies grow as workers learn to use more advanced capital goods, as long-term growth depends on the innovation[*]. Knowledge is the other asset that this economy produces. It can be thought of as outward shifts in the production possibilities frontier, and it is usually measured by changes in some index of total factor productivity (TFP), at the economy-wide level. Such changes are governed, according to Griliches (1998), first, by the application of new techniques (inputs and outputs from conscious efforts by scientists at home and abroad) and second, by the new knowledge diffusion through training and the introduction of new equipment. The representative country stock of ideas is described as $A_t \equiv \sum_{\forall j} A_{jt}$, where A_t is the average technological level of the economy in time t, below the technology frontier A_t^*. For the representative country we have that $A_t \leq A_t^*$.

A technological improvement results from a combination of two sources: imitation activities by adopting the world frontier technologies, and innovation on the local technological frontier, as in Eaton and Kortum (1996) and Vandenbussche *et al*. (2005). In this paper we assume researchers can work on both innovation and imitation, dealing as we are with economies on the frontier, or significantly near to it. The technological level of the economy depends on the number of researchers engaged in innovation and adoption activities, as well as the country's level of technology relative to the level of world knowledge. We assume that technologies are available worldwide for anyone to use. Thus,

$$A_{t+1} = \left[\delta L_{At}^{\lambda} A_t\right]^{\phi_1} \left[\mu L_{At}^{\lambda} \left(A_t^* / A_t\right)\right]^{\phi_2}, \qquad (2)$$

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[*] We are conscious that there is a timing lag related with the process of R&D, the discovering of new ideas and their implementation in productive activities (innovation in the sense of Schumpeter's). However, the consideration of innovation as a synonym of the discovery of ideas does not change the model implications or the results.

where the dependent variable A_{t+1} is the stock of knowledge tomorrow, L_{At} is employment in today's R&D sector [$L_{At} + L_{Yt} = L_t = L_0 \exp(nt)$], $\lambda<1$ captures the existence of decreasing returns from the scientific community in terms of new ideas, $\phi_1, \phi_2 \in (0,1)$ measures the sensitivity of the idea's stock to the research structure in innovation and diffusion processes respectively, and δ, $\mu \in (0,1)$ are constants of scale that multiply the explanatory variables.

This equation is growing in its arguments and it captures the two dimensions of technological progress. One source of such progress is the research activity and it is based on the local technology system. Its scope depends on the number of researchers (L_{At}) and their abilities at innovating (captured by λ). So, as more workers obtain a greater quantity of output in (1), more researchers may develop new ideas in (2). But the work of some researchers also involves adapting technologies at the frontier, because the discovery of new ideas usually implies a more complex process in order to find their applicability to the production of goods. Additionally, the process could also differ across countries. This task captures the capacity of a country to imitate, as a function of the work done in the R&D sector and it is also related with a catching-up term, represented by A_t^* / A_t. The catch-up term is consistent with Findlay (1978)'s relative backwardness hypothesis. The fact that λ, ϕ_1 and ϕ_2 may be different for each country, makes it possible for technology adoption to depend on the own effort made in R&D sector and not just on frontier displacement. Furthermore, the parameter δ can be interpreted as a measure of social infrastructures and the parameter μ represents the productivity of an economy in terms of transforming knowledge to new ideas (Jones, 2002b). Higher values of μ and δ will determine an improvement in the technological level of the country.

Researchers perform tasks of invention —a priority in firms that cannot afford to limit such activity to reproducing ideas already created, precisely because they are at the frontier -and of imitation or adaptation of new technologies, essential in businesses in economies that have fallen behind-. In this case, the stock of ideas at a moment in time, and in a particular country, is considered as a weighted geometrical average of the ideas generated by both processes in the past.

One interesting feature of the model is its adaptability to different specifications that can be nested. For example, if we impose some restrictions to the above equation, like $\phi_2 \rightarrow 0$ for firms at the frontier, the equation (2) becomes:

$$A_{t+1} = \left[\delta L_{At}^{\lambda} A_t\right]^{\phi_1}, \tag{3}$$

which has similar implications to the ones in Jones (2002a)'s function of ideas, at least in the long term. However, for companies in the more basic stages of research we can consider the parameter $\phi_1 \rightarrow 0$, then the equation (2) can be transformed into:

$$A_{t+1} = \left[\mu L_{At}^{\lambda}\left(A_t^{*}/A_t\right)\right]^{\phi_2}, \tag{4}$$

which recalls the functions of Nelson and Phelps (1966), Bils and Klenow (2000) and Jones (2002b). Additionally, it could be considered a wide range of intermediate situations between the two extremes, represented by equations (3) and (4), that any of them would reflect the position of each country with regard to the technological frontier.

A number of extensions of our model are worth exploring. First, if $\phi_1 + \phi_2 = 1$, equation (2) is reduced to a version of Papageorgiou (2003)'s specification:

$$A_{t+1} = \left[\delta L_{At}^{\lambda} A_t\right]^{\gamma}\left[\mu L_{At}^{\lambda}\left(A_t^{*}/A_t\right)\right]^{1-\gamma}, \tag{5}$$

where the $\gamma \in (0,1)$ represents the technology share

Second, the leader country may itself lie below the frontier. In this case, the function for ideas must be specified in terms of a non-observable component, the technological frontier. If the difference of the non-observable component follows a stationary process, equation (2) will admit a transformation in a state space form in order to apply the Kalman's filter for prediction. In order to treat specifically the evolution of the technological frontier, the expression (2) can be transformed, as suggested by Harvey (1989) and Hamilton (1994), in an augmented matrix with a random walk that captures the different technological frontiers among the economies.

Let Z_1, Z_2, ..., Z_t be the observations that account for the growth rate of the stock of ideas. They depend on another non-observable variable, the technological frontier, represented by ξ_t. The state space representation of the dynamics of an (nx1) vector Z is given by the following system of equations:

$$\begin{aligned} Z_t &= A'\mathbf{x}_t + H(z_t)'\boldsymbol{\xi}_t + \mathbf{w}_t \\ \boldsymbol{\xi}_{t+1} &= F\boldsymbol{\xi}_t + \mathbf{v}_{t+1} \end{aligned}, \tag{6}$$

where *A'*, *H'* and *F* are matrixes of dimension (*n*x*k*), (*n*x*r*) and (*r*x*k*) respectively, x is a (*k*x1) vector of exogenous or predetermined variables (the number of researchers and the stock of ideas), ξ is a (*r*x1) vector of unobserved *state variables*, and the disturbance vectors w and v are assumed to be stationary and i.i.d, with $\text{var}(w_t) = R$, $\text{var}(v_t) = Q$ and $E(w_s v_t) = 0,\ \forall\ s,t$. The relation between Z_t and ξ_t is linear and is specified by the first expression in equation (6), which is known as the *observation* equation. The dynamic nature of the system is incorporated through the second equation, which is known as the *state* equation. In general, the elements of ξ_t can not be observed, but it is known that can be generated by a first order Markov process.

The growth rate of the stock of ideas has to be constant at the balanced growth path. Taking logarithmic and derivatives in equation (2), we obtain the growth rate of *A* at the balanced growth path:

$$\bar{g}_A = \lambda\{(\phi_1 + \phi_2)n + [\phi_2/(1-\phi_1)]n^*\}/(1+\phi_2-\phi_1), \tag{7}$$

where n^*, n are the exogenous growth rates of labour in the leading and following countries respectively. We can easily get the steady-state growth rate of the follower country from (5) as

$$\bar{g}_A = \lambda(n+n^*)/2(1-\gamma), \tag{8}$$

which in the case of the leader becomes

$$\bar{g}_{A^*} = \lambda n^*/(1-\gamma). \tag{9}$$

An interesting feature of these results is that the long-run growth rate does not depend on the number of researchers, but on the elasticity's of the idea's functions and on the population growth rate. To the extent that these parameters could be, in principle, unaffected by policy, we can establish that the long-run growth rate behave invariant to standard policy changes[†].

3. Empirical Analysis

Once we have constructed different alternatives of the model, our main objective consist in examining whether our theory fits with the technical progress disparity observed across countries. We test the equation (2) and the system of equations (6) using cross-section data applied to four leading countries: France, Germany, United Kingdom and US. The temporal horizon covers from 1950 to 2001. After discussing the different sources of the data, we present alternative specifications tested by employing ordinary least squares (OLS) and

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[†] A further discussion about this result is available in Jones (2005).

the maximum likelihood estimator (MLE) to find the best approach to the technology growth equations specified in the above sections.

3.1. Data Description

The main features about the data and the construction of variables are emphasized here; the Appendix also describes in detail the data sources. In Jones (2002a), labour productivity y_t is shown as:

$$y_t = \left(K_t / Y_t\right)^{\alpha/(1-\alpha)} l_{Yt} h_t A_t^{\sigma/(1-\alpha)} \tag{10}$$

where Y_t is production of goods and services, K_t the stock of physical capital, l_{Yt} the proportion of the workforce allocated in the production of goods, h_t human capital per person and A_t the stock of ideas available at the economy. Most of the counterparts are reading observed. The elasticity of capital with respect to income α is assumed to be equal to 1/3, in line with the most representative literature, Mankiw *et al.* (1992), Mankiw (1995) and Gollin (2002) among others. Mincer (1974)'s specification, $h_t = \exp(\psi l_{ht})$, assumes that the endowment of human capital per person is a function of the time devoted to training (l_{ht}), and it is measured by the average years of education of the fraction of population over 25. The data comes from De la Fuente and Doménech (2006). The Mincer (1974) results on the return on education suggest a value ψ=7% and Jones (2002a) assumes $\sigma = 1/(1-\alpha)$.

The endogenous variable is the stock of ideas, which is measured by TFP and derived from equation (10) in the same spirit as Solow's classic growth accounting model. The explanatory variables are: the level of knowledge for each country relative to the world technological frontier, and the number of scientists and engineers engaged in R&D activities. Table 1 displays the list of the aforementioned countries along with a complete data summary regarding labour productivity, TFP and research intensity.

[TABLE 1 *HERE]*

We use the GDP per hour worked as a proxy for the productivity variable. The US labour productivity grew at a lower rate than that of European countries between 1950 and 2001. The average data for Germany and France, which stood at 29% of the US productivity data in the middle of the last century, had increased to 66% by the end of the century. Thus, the catching up rate grew at 1.64% relative to the leader economy. By the other side, TFP average grew from 33.8% to 65%, catching up the US economy at a rate of 1.3%. Finally, we decided to employ an input measure to capture the research intensity. We use the data available from the

OECD in the terms of the number of researchers as a proportion of the labour population. Nevertheless, there are some missing data that we have obtained by interpolation. The figures show that United States accounts the highest research intensity during the whole period, followed by Germany, France and the United Kingdom in 2001.

3.2. Estimation

We estimate the equation (2) that accounts for the production and diffusion of technology and, as we can observe, it depends positively on its arguments. In this equation the stock of ideas in t+1 could be expressed as a function of today's technological effort, as well as a function of the technological distance from the technology frontier. We consider two possible scenarios: first, the one in which the technological frontier is known, and second the non-observable scenario.

3.2.1. The Frontier of the United States

We assume that the technological frontier has been established by US, $A_t^* = A_t^{US}$. Thus, the distance to the frontier is defined as the ratio of the US stock of ideas related to the stock of ideas for the follower country. Taking logarithms in (2), in lower case, and subtracting a_t on both sides of the equation, we obtain a log-linear approximation of the growth function of ideas in a discrete-time version. The dynamics of the stock of ideas is expressed as:

$$\Delta a_{t+1} = \beta_1 + \lambda(\phi_1 + \phi_2) l_t + (\phi_1 - 1) a_t + \phi_2 \left(a_t^{US} - a_t\right) + \varepsilon_{t+1}, \qquad (11)$$

where $\beta_1 = [\phi_1 \log(\delta) + \phi_2 \log(\mu)]$ is a constant, and ε_{t+1} is a shock that is generated by a stationary process with zero mean. Equation (11) relates each country's technical progress positively to its research effort, to country's level of technology and to their level of technology relative to the leader. The β_1 term stands for δ and μ, reflecting the impact of social infrastructures for inventiveness and technology adoption. We treat the right hand side variables as exogenous. The dependent variable is the TFP growth rate and the explanatory variables enter in logarithms, and so they are expected to have a direct effect on the endogenous variable.

In what follows in this section, we are interested in the values of three parameters: λ, ϕ_1 and ϕ_2. The first coefficient represents researcher performance, the second the effect of old ideas on new ones and the third the convergence rate. One source of technological progress in non-leader countries is the adoption of frontier technologies, captured from (11) by $\phi_2\left(a_t^{US} - a_t\right)$. If the value of coefficient ϕ_2 is high (and positive) the non-leader country performs better the greater the technological distance. But when the catching up term approaches zero the accumulation of skills becomes slower (and expensive). Then the rate of aggregate technology is managed mainly by the binomial $\lambda\phi_1 l_t + (\phi_1 - 1)a_t$, and the country may increase growth by increasing the number of researchers working on innovation.

Table 2 reports the OLS estimation, as well as the SUR system with parameter constraints that does not provide efficiency gains. The model offers a fairly satisfactory explanation of the way technological progress evolves. More so, even, taking into account that process is contaminated by the cycle. In Germany, the equation explains over 75% of the variance of the dependent variable and in France 43%, while the proportions achieve roughly 17% in the Anglo-Saxon countries. These results imply that the diffusion of ideas is the major vehicle to absorb technology leaving behind the inventiveness in the following countries. The results also show the existence of positive association between the distance to the frontier and growth rate in Germany and France (though not in the United Kingdom). The magnitude of the estimated coefficients ϕ_2 entails that TFP is converging towards technology frontier at a rate of about 12% a year in these countries. This is the "premium" which, in terms of growth, these countries obtain by being sited below the frontier.

[TABLE 2 HERE]

However, in the US the coefficients reflect the effect of innovation that is significant at the 1% level. The λ and ϕ_1 parameters have the correct sign and they are consistent with Jones (2002a). These values suggest a close link between researchers and the growth of the stock of ideas in the US economy, circumstance that is not clearly appreciable in European countries, as Perez and Esteve (2007) and Myro *et al*. (2007) point out. Thus, imitation is the only source of technology progress in those countries and the diffusion mechanism facilitates variations in the catching-up parameter[‡]. Even so, it is difficult to accept that the research activity is

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[‡] With $\phi_2 \neq 0$, and $\phi_1 > 0$ by construction, $\lambda\left(\phi_1 + \phi_2\right) = 0$ requires $\lambda = 0$ in Germany and France.

not important in economies close to the frontier, so the constrained model from equation (5) is estimated below:

$$\Delta a_{t+1} = \beta_2 + \lambda l_t + 2(\gamma - 1)a_t + (1-\gamma)a_t^{US} + \varepsilon_{t+1} \ , \tag{12}$$

where $\beta_2 = \left[\gamma \log(\delta) + (1-\gamma)\log(\mu)\right]$ is a constant.

Table 3 shows the results, being clearly that the coefficients for the United States are identical to those showed in Table 1. In the first place, the λ parameter for impact of R&D employment on idea's growth has the expected sign and it is significant at the 1% in Germany and Great Britain, and at the 5% in US (although not in France). Furthermore, it is not possible to reject the null hypothesis of equal coefficients, particularly between Germany (λ=0.034) and UK (λ=0.027, standard error =0.01 in both cases). The magnitude of the λ coefficients imply that, due solely to its higher level of researcher performance, the US absorbs about 2/3 times as much technology as Germany and two fold as the UK. Secondly, γ share parameter also has the right sign and is different from zero at the 1% significance in the four countries.

[TABLE 3 HERE]

The estimated β_2 parameter captures the effect of social infrastructures and any other additional factors which contribute to the technology growth. To understand its role let us focus on the equation below that is true from specification (4):

$$\frac{A^*}{A} = \frac{A}{L_A^{\lambda}} . \frac{1+\bar{g}_A}{\mu} \ . \tag{13}$$

$\frac{A}{L_A^{\lambda}}$ ratio can be treated as a constant in the long-run and the dynamic of $\frac{A^*}{A}$ involves only one dimension, corresponding to $\frac{1+\bar{g}_A}{\mu}$. Thus, the higher the μ parameter value, the closer is a country's technology level to the frontier.

3.2.2. The Unknown Frontier Scenario

Our estimates of the idea's stock growth equations suggest that our model captures some of the major determinants in the international technology enhance. These parameters should have important consequences for the behaviour of technology across leading countries. In order to examine these effects and to sharpen our estimates we now estimate the growth of the stock of ideas equations under the hypothesis that technological frontier does not lay on USA. Implicit in the unknown frontier scenario is the hypothesis that, at some level, technologies are available all over the world for everyone to use.

Under the hypothesis that the frontier does not coincide with the US, our aim is now to estimate from (6) the parameters of interest and make inferences about ξ, given observations of (Z_t, x_t) for t = 1, 2, 3,....,T, using Kalman's filter. In order to estimate the system we express it in vector form. Hence, the representation of the non-constrained model in space state for any country yields:

$$\begin{aligned} \Delta\mathbf{a}_t &= \boldsymbol{\beta}_1 + \lambda(\phi_1 + \phi_2)\mathbf{l}_{t-1} + (\phi_1 - \phi_2 - 1)\mathbf{a}_{t-1} + \phi_2\boldsymbol{\xi}_t + \mathbf{w}_t \\ \boldsymbol{\xi}_{t+1} &= \beta_2\boldsymbol{\xi}_t + \mathbf{v}_{t+1} \end{aligned} \tag{14}$$

Incorporating constrains in the restricted system of equations gets

$$\begin{aligned} \Delta\mathbf{a}_t &= \boldsymbol{\beta}_1 + \lambda\mathbf{l}_{t-1} + 2(\gamma - 1)\mathbf{a}_{t-1} + (1-\gamma)\boldsymbol{\xi}_t + \mathbf{w}_t \\ \boldsymbol{\xi}_{t+1} &= \beta_2\boldsymbol{\xi}_t + \mathbf{v}_{t+1} \end{aligned} \tag{15}$$

In this set up, the first equation of (14) and (15) systems defines the technological progress and the second one the evolution of the frontier. The parameters are time-varying coefficients that enable us to assess the dynamic evolution of asymmetries. Coefficient β_1 is a stochastic constant that approximates all those factors that have a systematic influence on the variables and F≡β_2 is a real (scalar) number. The world technological frontier is assumed to follow an AR(1) process and a constant mean. This hypothesis corresponds with our belief that shocks to the random coefficients, although quite persistent, eventually return to their mean values.

The parameters of both system of equations are estimated by maximising the log likelihood function under the assumption that the distribution of Δa_t, conditional on (l_{t-1}, a_{t-1}) and their past value, is multivariate normal. Under regularity conditions, the MLE is asymptotically efficient, as Green (2003) points up.

Table 4 reports the results for non-constrained model (14). The MLE estimation of technology parameters differ greatly from the OLS estimation in Table 2. One difference is that the λ coefficient on inventiveness performance is now significant in all countries. In the US is three times bigger. Nonetheless, the differences remain large across countries: due to more productivity, US researchers produce on average three fold as much technology as do the Germans, and six fold as do the French and the British. A country's total inventive output is proportional to the factor of these coefficients, so the range of variation between the United

States and the European countries is much bigger. The results are in broad agreement with those obtained by Eaton and Kortum (1996).

[TABLE 4 HERE]

A second difference from OLS estimations is that sensitivity to the ϕ_1 innovation parameters are now of correct sign and precisely estimated, despite the fact that differences stay large across countries. The coefficients vary between 0.53 for the US to 0.75 for the European countries, with standard errors less than 0.08. These estimations imply that the United States pay half more attention to diffusion of ideas as Germany, France and the United Kingdom do, which are very similar. Nevertheless, the sensitivity of ϕ_2 imitation parameter is unstable across specifications and imprecisely estimated. The model performs well, as it explains a higher percentage of the variance of the dependent variable.

Results from table 5 are broadly similar to those obtained in Table 4, although they offer a more satisfactory explanation of the variance in technological progress rate. It is now 99% in the United States, meanwhile remains fairly unchanged in the other countries. As a result, the unknown frontier scenario offers a better account of ideas evolving than the US frontier scenario.

[TABLE 5 HERE]

Figure 1 shows the dynamic of the states of nature (15), where the forecast estimates of the ξ_t's are plotted. The random coefficient vector $\boldsymbol{\xi}_t = \boldsymbol{\beta}_t - \bar{\boldsymbol{\beta}}$ is the state of nature, where $\bar{\boldsymbol{\beta}}$ is the steady-state value of the coefficient vector if the process is stationary. As is clear from the figure, the actual values of the US frontier fluctuate very closely around its balanced growth path. However, correlation does not seem to be as close between European countries as it is in the US.

[FIGURE 1 HERE]

V. Implications

We now examine some implications of our results. We first discuss the sources of growth in the economies and then we turn to the inventiveness and its determinants. We conclude with a counterfactual experiment. Except where indicate otherwise, our analysis is based on the parameters estimates from the restricted models.

What do our estimations imply about the sources of technical progress growth in European economies using the US frontier scenario? Combining our estimations for innovation and imitation activities allow us to ascribe the share of each country growth coming from innovation or imitation. The results suggest that, while there is a tendency for US to invent ideas, the tendency is not overwhelming. In European leading countries, the share of total technological growth based on national research averages roughly 37%, varying from 33% in UK to 41% in Germany.

What do our results imply about researcher performance in terms of creation on new ideas? Our results imply that, in a world integrated market, American researchers are more efficient than their European counterparts in the creation of new ideas. Therefore, the results observed in Table 4 suggest that imitation is the main source of technological progress in those countries[§]. These findings are not robust to alternative definitions of the technological frontier. Additionally, our empirical estimations provide some interesting insights. In the United States, the elasticity of TFP growth with respect to researchers is 50% higher than in Germany and double the one for the UK. To better understand the importance of these differences, we have simulated how changes in λ influence the transitional growth path in Germany. On one side, a uniform increase of 5% works out in a higher growth path, which in turn leads to a higher steady-state than the baseline path. On the other, Figure 2 shows that, in this scenario, the German idea stock (thin line) tends to catch up with that of the US, everything else being equal.

[FIGURE 2 HERE]

What would happen if technological frontier didn't coincide with the US? We can make use of our estimations to consider the consequences for technical progress growth and relative productivity of enlarging world technological frontier. Since American researchers double its performance, the impact on its steady-state growth rate is significant, rising from 0.3 to 0.7%. The greater the production frontier, the more new ideas researchers generate on average. The hypothesis of a frontier that surpasses the US boosts the performance and the dispersion of the R&D workforce. Moreover, US productivity increases relative to every country except the United Kingdom by more than 50%. US researchers are the most efficient, with productivity levels on occasion eight times higher than French researchers and twice that of their German counterparts. One implication of this last statement is that international trade of ideas is a major factor of technology in leading

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[§] The parameter λ is equal to 0.211 in this case.

countries other than the United States: European countries rely on innovations from the US for over 55% of its total growth. Furthermore, with a larger stock of ideas than any other country, US also has a larger proportion of researchers involved in the diffusion of knowledge.

VI. Conclusion

In this paper, we have developed a model of invention referring to the technology diffusion across countries. We consider two alternative scenarios: one in which the technology frontier lays on the US, and another where it transcends the world technological leader and is unknown.

Our model implies that, in worldwide integrated markets, countries technology will grow with a country's relative productivity, stated by its capability to make new inventions and to adopt its own and others' inventions. An implication is that at national (no-integrated) markets, where one country's researchers and scientists might do both R&D activities, the innovation-imitation ratio might lead to a situation where the reassignment of resources would not respond to the productivity criteria. As a result the potential technological growth would be smaller.

We test the model for four different economies: United States, France, Germany and UK, covering the second half of the 20th century. The technology output of the countries is highly correlated with the scale of its economy and its research community. American researchers are more growth enhancing than their European counterparts, so these countries rely on innovations from the US for over 55% of its total growth. The hypothesis of an unknown frontier scenario entails that US innovating yield increases between twofold and fourfold and the steady-state growth rate rises from 0.3 to 0.7%. Another interesting feature of the technological frontier displacement is that the share of researchers engaged in technology diffusion increases by a third. Therefore, as a country gets closer to the frontier, it relocates R&D labour from imitation to innovation.

Our results suggest that future research has to be taken about the role of infrastructure and the human capital to explain the smaller performance in terms of technological productivity of Europe, as they devote more resources to innovation activities and similar number of scientifics than in the US, but their results are far away from the Americans. Also, some of these differences come from the sources of financial support (private funds *versus* public funds) and the way they could induce the creation of new ideas.

Acknowledgements

We would like to thank Angel de la Fuente, Rafael Domenech, Adolfo Maza, Rafael Myro and Xavier Sala-i-Martín for their useful suggestions and comments. The usual disclaimer applies.

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Appendix: Data Sources

- *GDP per Hour*. The data for GDP at 1990's constant prices were calculated using Eurostat (Statistical appendix to European Economy). The values corresponding to the period 1950-1960 are based on the GDP Movement series provided by Maddison (1995). 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 UK.
- *Human Capital*. The data for average years of educational training for population over 25 come from De la Fuente and Doménech (2006).
- *Engineers and Scientists Engaged in R&D activities*. The source (National Science Board and OECD) is the same as in Jones (2002). The figures for Germany until 1989 are the sum of the old Federal and Democratic Republics. For the years prior to 1960, it was assumed that the ratio of "research intensity" for the three European countries in relation to the US was the same in 1950 as in 1960. This ratio was interpolated for the intermediate years and then multiplied by employment.
- *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. In contrast, the series for the preceding years, 1950-1960, is the result of deducting the annual variations provided by Maddison (1995) from the number of people employed in 1960.

Table 1. Summary Tabulation

		DE	FR	UK	US
Productivity [a]	1950	4.0	4.4	5.4	14.4
	2001	27.1	25.1	16.9	39.5
TFP	1950	1.3	1.7	2.6	4.6
	2001	6.5	6.5	4.7	9.9
Research	1950	0.08	0.08	0.10	0.27
Intensity	2001	0.85	0.74	0.58	1.00

US = 100

		DE	FR	UK	US
Productivity [a]	1950	27.5	30.5	37.8	100
	2001	68.7	63.6	42.8	100
TFP	1950	28.3	37.9	56.8	100
	2001	65.4	65.1	47.5	100
Research	1950	30	30	37	100
Intensity	2001	85	74	58	100

Notes: [a] Output per worker ($/hour, PPP of 1995).

Table 2. Innovation and imitation: non-constrained model

Dependent variable is the technological growth rate

Estimation Method: Least Squares

Coefficients	DE	FR	UK	US
β_1	-0.096	-0.042	-0.090 *	-0.022
	(0.06)	(0.07)	(0.05)	(0.04)
$\lambda(\phi_1+\phi_2)$	0.021	-0.021	0.019	0.056***
	(0.02)	(0.03)	(0.02)	(0.02)
ϕ_1-1	−0.030	0.064	-0.044	-0.163***
	(0.06)	(0.08)	(0.06)	(0.06)
ϕ_2	0.128 *	0.121 *	0.106	
	(0.06)	(0.07)	(0.08)	
λ implicit				0.067***
				(0.02)
R^2	0.75	0.45	0.13	0.17
DW	1.85	2.01	1.68	2.02

Notes. Standard errors, robust to the heteroscedasticity according to Newey-West, are in brackets. ***, ** and * indicate statistical significance at the levels of 1, 5 and 10% respectively. The standard error of λ implicit in the US was calculated by the delta method.

Table 3. Innovation and imitation: constrained model

Dependent variable is the technological growth rate

Estimation Method: Least Squares

Coefficients	DE	FR	UK	US
β_2	-0.057	0.017	-0.072 *	-0.022
	(0.03)	(0.04)	(0.04)	(0.05)
λ	0.034***	0.009	0.027***	0.056 **
	(0.01)	(0.01)	(0.01)	(0.02)
γ	0.922***	0.967***	0.931***	0.837***
	(0.01)	(0.01)	(0.02)	(0.06)
R^2	0.75	0.44	0.13	0.17
DW	1.78	1.93	1.66	2.02

Notes. Standard errors, robust to the heteroscedasticity according to Newey-West, are in brackets. ***, ** and * indicate statistical significance at the levels of 1, 5 and 10% respectively.

Table 4. State space non-constrained model

Dependent variable is the technological growth rate

Estimation Method: Maximum Likelihood

Coefficients	DE	FR	UK	US
λ	0.066^{**}	0.031^{*}	0.032^{*}	0.211^{***}
	(0.03)	(0.02)	(0.02)	(0.08)
ϕ_1	0.715^{***}	0.795^{***}	0.750^{***}	0.531^{***}
	(0.07)	(0.03)	(0.06)	(0.08)
ϕ_2	0.001	0.001	0.001	0.001
	(0.00)	(0.00)	(0.00)	(0.00)
R^2	0.59	0.67	0.37	0.44

Notes. Standard errors are given in brackets. ***, ** and * indicate statistical significance at the levels of 1, 5 and 10% respectively. Parameters common to the four countries have the values: $\beta_1 = 0.144^{***}$ (standard error = 0.04), $\beta_2 = 1.018^{***}$ (standard error = 0.02) and logarithm of the likelihood function equal to 425.7.

Table 5. State space constrained model

Dependent variable is the technological growth rate

Estimation Method: Maximum Likelihood

Coefficients	DE	FR	UK	US
β_1	0.046	0.055***	-0.134***	-0.110***
	(0.04)	(0.01)	(0.05)	(0.06)
λ	0.040 **	0.015 *	0.104***	0.128***
	(0.02)	(0.01)	(0.02)	(0.02)
γ	0.929***	0.967***	0.871***	0.821***
	(0.01)	(0.01)	(0.02)	(0.02)
R^2	0.60	0.42	0.16	0.99

Notes. Standard errors are given in brackets. ***, ** and * indicate statistical significance at the levels of 1, 5 and 10% respectively. Parameters common to the four countries have the values: $\beta_2 = 0{,}362^{**}$ (standard error = 0.17) and logarithm of the likelihood function equal to 485.4.

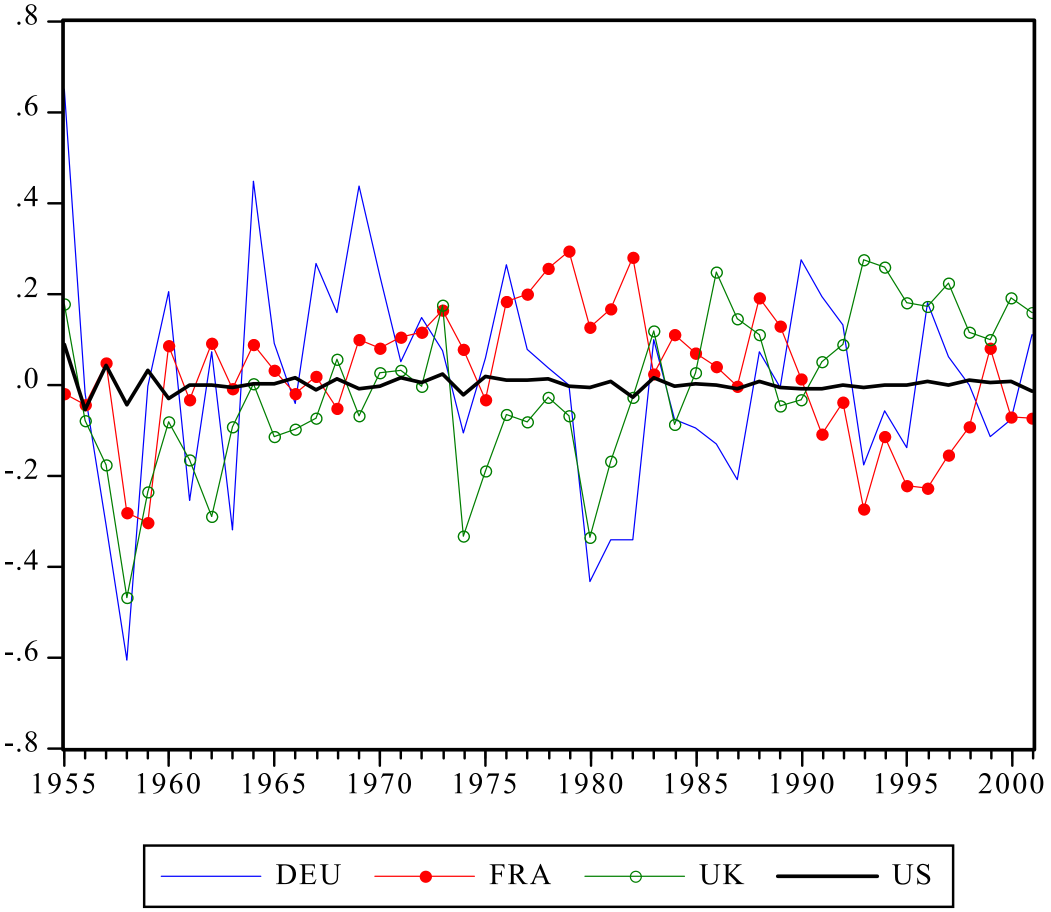

Fig. 1. Simulated values of the state of nature $\xi_t = \beta_t - \bar{\beta}$ at time *t*, via the Kalman filter. As is clear from the figure, the actual values of the US frontier fluctuate very closely around the steady state.

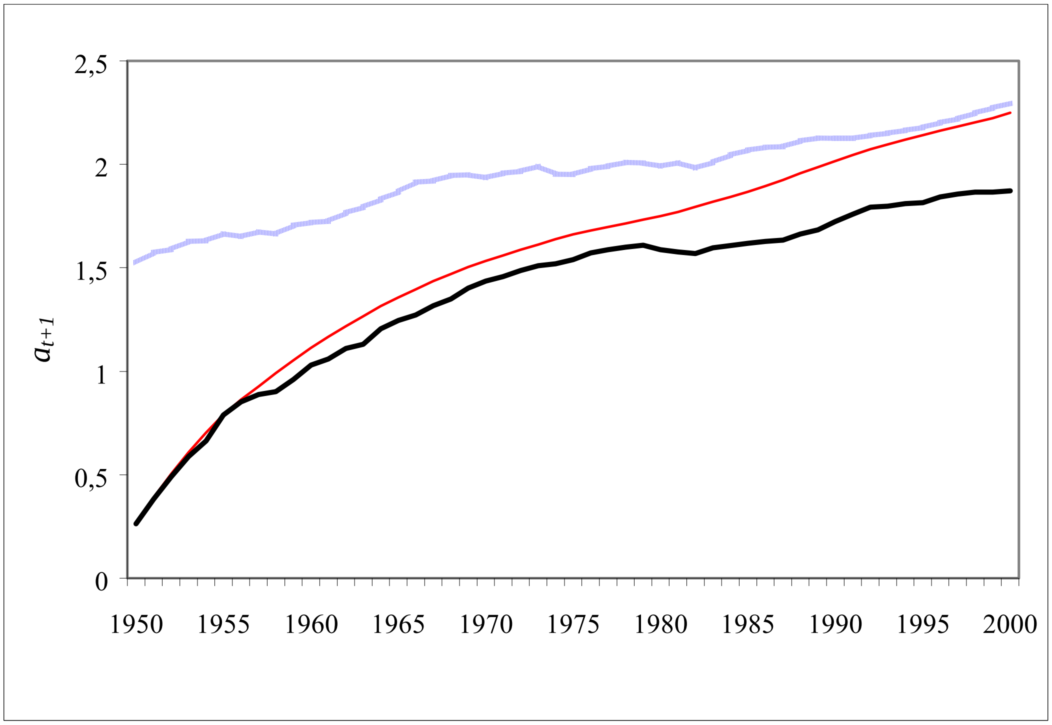

Fig. 2. Catching up of the stock of ideas in Germany with that of the US frontier: baseline (thick line) and simulated path of a 5% increase in the yield of researchers (thin line).