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Abstract

Trade in goods and services is likely to be an important channel for international knowledge diffusion. This paper considers the extent of R&D spillovers through intermediate inputs for a sample of up to 40 developed and developing countries. Results suggest that such spillovers are present and are economically important. We find that countries and industries initially further behind the technological frontier enjoy stronger foreign R&D spillovers. Furthermore, foreign R&D spillovers are stronger in countries with greater absorptive capacity as measured by average years of secondary schooling and R&D spending. In terms of absorption barriers, the results are mixed: With the exception of regulations on temporary workers we find that stronger labour market regulation and greater union density is associated with lower foreign R&D spillovers. The evidence for other absorption barriers related to product market, financial and investment regulation provide however no evidence of low regulation encouraging foreign R&D spillovers, with - in some cases - the reverse being found to hold true. Finally, we find that stronger levels of IPR protection can limit the extent of foreign R&D spillovers, possibly by limiting the ability to copy and borrow technology from abroad.

Keywords: R&D spillovers, intermediates trade, productivity

JEL classification: F15, O14, O19

CONTENTS

TABLES AND FIGURES

1. Introduction

The importance of technology for raising productivity and living standards has long been recognised. This is reflected in the modern literature on economic growth, in which technological progress is viewed as the prime determinant of long-run growth. In these models technological progress arises from the R&D activities of economic agents carried out in order to profit from the introduction of new products (Romer, 1990) or the improvement of existing ones (Aghion and Howitt, 1992). More broadly, technological progress encompasses changes in production processes, organisational structures, management techniques and the like that raise productivity. Resources for such innovation tend to be highly concentrated in a small number of advanced OECD countries,[1] which have the requisite skills and institutions in place to undertake innovation and invest heavily in R&D. As a result firms in these countries register the bulk of patents. For countries whose firms are not at the technological frontier, the diffusion of technology from the frontier is likely to be an important source of productivity growth, through both imitation and also through follow-on innovation and adaptation (Evenson and Westphal, 1995). International technology transfer or diffusion refers to the process by which a firm in one country gains access to and employs technology developed in another country. Some transfers occur between willing partners in voluntary transactions, but much comes through non-market transactions or spillovers. Technology flows across borders via a number of formal and informal channels, making measurement difficult. Knowledge would be expected to flow across borders through a number of channels including international trade (both imports and exports), FDI, licensing, joint ventures, imitation and reverse engineering and through data published in patent applications.

Trade in goods and services is likely to be an important formal channel for international knowledge diffusion, with imports of goods having the potential to transfer knowledge through reverse engineering, but also through the cross-border learning of production methods, product design, organisational structure and market conditions. Trade in capital and intermediate goods in particular is likely to be an important source of technology diffusion in this way. Exports are also likely to be an important channel for technology diffusion. Grossman and Helpman (1991) for example argue that sellers gain from the knowledge base of their buyers, especially where buyers suggest ways to improve the product or the process of manufacture. A second formal channel of diffusion is FDI, and inward FDI in particular, with Multinational Companies (MNCs) expected to deploy advanced technology to their subsidiaries that may be diffused to host-country firms. Licensing, which involves the purchase of production and distribution rights for a product and the knowledge required to make effective use of these rights, is a further channel for technology diffusion. Joint ventures combine many of the properties of FDI and licensing and hence will also involve technology transfer. The movement of skilled workers across borders can act as a channel for international technology diffusion. These formal channels of technology diffusion are likely to be interdependent, with firms making their decision on which channel(s) to serve foreign markets based on the expected return to their technological assets.

Informal channels of technology diffusion include imitation; the movement of personnel from one firm to another taking with them specific knowledge of their original firm's technologies; data in patent applications and the temporary migration of people, such as scientists and students to universities and research institutes in advanced countries. What is specific to the informal channels, and is part of their

[1] The share of R&D financed by enterprises in advanced countries was 98% in the 1980s and 94% in the 1990s (UNIDO, 2002). Even within developed countries however R&D is concentrated, with Eaton and Kortum (1999) noting that in the late 1980s, 80% of OECD research scientists and engineers were employed in five countries (US, UK, Germany, Japan and France).

attraction, is that there is no formal compensation to the original owner of the technology transferred. But there will still be costs. Imitation for example requires resources that may be drawn from local innovation.[2] The formal and informal channels are also related. It is likely that in order to be able to reverse engineer and imitate advanced technology some level of trade or temporary migration is required for example. The interdependence among formal channels and between formal and informal channels raises difficult issues for empirical studies.

While considered to be an important source of productivity growth, the measurement of technology is not straightforward given its nature as an intangible asset. A number of alternative measures have been employed in the empirical literature, though all have their disadvantages. Keller (2004) discusses the advantages and disadvantages of a number of these measures, including data on R&D expenditures, patent count data and measures of technological change based on Total Factor Productivity (TFP) data.

Since technology itself is difficult to measure, we also tend to find that measures of technology diffusion are imperfect. Several approaches have been employed[3]. One approach, following the seminal contribution of Coe and Helpman (1995), has been to examine whether R&D conducted in one country (and/or industry) impacts upon TFP in other countries (and industries). The starting point for this kind of analysis is to construct a stock of knowledge for each country (industry) using past R&D expenditures and then to weight these stocks by some variable indicating the access that other countries (industries) have to this knowledge. Weights used in the literature include imports (Coe and Helpman, 1995; Coe, Helpman and Hoffmaister, 1997), capital goods imports (Xu and Wang, 1999), inward and outward FDI (Xu and Wang, 2000), exports (Funk, 2001; Falvey, Foster and Greenaway, 2004), and intermediate input flows (Nishioka and Ripoll, 2012).

A second approach has been to use patent count data. While the decision to patent results in the publishing of the technical information relevant to the patent, as discussed above, Eaton and Kortum (1996) also argue that the decision of *where* to patent affords further information regarding where innovators see their ideas being used. Since patent laws are national in scope and since obtaining patent protection is costly, inventions are typically only patented in a small number of countries. Eaton and Kortum argue that this choice of where to patent is determined by market size and by where the invention is likely to be useful. They use a cross-section of 19 OECD countries to explain the number of patents taken out in one country (destination) by inventors in another country (source). The results suggest that technology diffusion is larger, the smaller the distance between two countries, the larger the ability of the destination to absorb technology (as measured by the level of human capital), and the higher the relative productivity of the destination. A higher ratio of imports to GDP is not always found to facilitate the diffusion of knowledge.

A third approach that has proved popular in the growth literature more broadly, has been to follow Nelson and Phelps (1966) who argue that the rate of technology absorption depends upon the 'technology gap', usually measured by the ratio of GDP per capita of a country to that of the technological leader (usually the US). Benhabib and Spiegel (1994), for example, regress the growth rate of GDP on standard variables including the interaction between the technology gap and a measure of human capital. They find a positive and significant coefficient on this interaction term and conclude that human capital speeds the adoption of foreign technology.

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2 Mansfield et al. (1981) show that the costs of imitation while lower than the cost of innovation are significant. Patenting innovations was found to raise the costs of imitation further, though even for products that were patented, 60% were imitated within four years.

3 See Keller (2004) for a review of the evidence on international technology diffusion.

2. Existing empirical evidence

Given difficulties in measuring technology and technology diffusion, the majority of empirical work in this area concentrates on a particular channel of diffusion and examines the extent of interaction between countries via this channel and its impact upon measures of economic performance at either the aggregate or firm-level. While we have seen that technology may diffuse through numerous channels, international trade has been emphasised in much of the empirical literature as being a significant source of technology diffusion.

Coe, Helpman and Hoffmaister (1997) identify four channels through which knowledge produced in one country and transmitted through imports can affect productivity and growth in others: Firstly, through the importation of intermediate and capital goods which may enhance the productivity of domestic resources; Secondly, through the cross-border learning of production methods, product design, organisational structures and market conditions that can result in a more efficient allocation of domestic resources; Thirdly, through the imitation of new products; and finally through the development of new technologies or the imitation of foreign technology. Exports are also likely to play an important role in international technology diffusion. Exports are likely to be an important channel of information flows with overseas buyers sharing knowledge of the latest design specifications and production techniques that might otherwise be unavailable, as well as providing a competitive environment, in which efficiency advantages can be obtained. Such effects may be observable at both the aggregate and firm/plant-level and this is reflected in the empirical work that has taken place. For the purposes of this study however, we concentrate on the literature at the aggregate level.

Coe and Helpman (1995) examine the impact of international R&D spillovers and the importance of imports in facilitating these spillovers for 22 OECD countries. They construct a stock of R&D for each country in their sample using past R&D expenditures. A measure of the stock of foreign knowledge that is available to each destination country is then constructed by weighting the R&D stocks of its source (exporting) trade partners by the bilateral import shares. TFP is then regressed on both the foreign and domestic stocks of knowledge.[4] The results suggest that both domestic and foreign knowledge stocks are important sources of productivity growth, although the former has a much larger impact in the larger countries. Smaller countries it is argued tend to be more open and benefit to a greater extent from foreign knowledge spillovers.[5]

The initial results of Coe and Helpman (1995) proved to be controversial. Keller (1998) compared the results of Coe and Helpman (1995) with those from assigning bilateral trade partners randomly and found that regressions based on simulated data generated on average larger estimated foreign knowledge spillovers and a better fit. Coe and Hoffmaister (1999) note however that Keller's bilateral import shares are similar to equal weights, or simple averages of trading partners' knowledge stocks, suggesting that Keller's weights are not in fact random. Using alternative random weights, Coe and Hoffmaister (1999) find that the estimated foreign knowledge spillovers are extremely small and present

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4 In their preferred specification the stock of foreign knowledge is interacted with the overall import share to take account of the level as well as the distribution of imports.

5 This outcome is not replicated when patent count data are employed, however. Eaton and Kortum (1996) find only limited evidence of a role for imports in facilitating technology diffusion among OECD countries as mentioned above.

a poor fit. They conclude that using bilateral import weights or simple averages perform better than random weights suggesting that a country's productivity is related to its trading partners' knowledge stock, but concede that the actual intensity of the trading relationship may not be that important due to the public good nature of knowledge. In addition, while Coe and Helpman (1995) argue that there exists a cointegrating relationship between their variables, allowing them to consider the relationship in levels without having to transform the data they choose not to report t-statistics for their results since at the time of writing the paper the asymptotic distribution of the t-statistic was not known. Kao et al. (1999) argue that since the estimated coefficients are small it is not clear whether they are significant. They use non-stationary panel techniques examine whether there are indeed significant foreign knowledge spillovers. They find that while the coefficient on the spillover variable remains positive, it is not significant.[6]

This type of analysis has been extended to consider North-South foreign knowledge spillovers by Coe, Helpman and Hoffmaister (1997) who find evidence that spillovers from the advanced North to the developing South are also an important source of productivity growth, with imports again being an important channel for such diffusion. The approach has also been extended to the industry level (e.g. Keller, 2000) with positive R&D spillovers again found at the industry level. Different trade weightings have also been used in the literature, with Xu and Wang (1999) using capital goods imports as weights rather than total imports and Funk (2001) and Falvey et al. (2004) employing export rather than import data. A further extension of the literature has been to consider the possibility of indirect spillovers through imports. This raises the possibility that country A can benefit from the R&D undertaken in country C even if it does not trade with this country. This would occur if country A imported from country B, which in turn imported from country C. Lumengo-Neso et al. (2005) capture this indirect effect and find that the results provide stronger evidence of trade-related R&D spillovers than found by Coe and Helpman (1995). Such results support the view that indirect spillovers are important. In a recent contribution Nishioka and Ripoll (2012) capture the direct and indirect effect of intermediate inputs using input-output tables (see below for more details).

Despite the controversy Keller (2004) concludes that overall the evidence points to a significant role for imports in the diffusion of foreign knowledge. This is particularly the case when one considers extensions to the literature such as Lumenga-Neso et al. (2005) and Xu and Wang (1999) who use capital goods imports rather than overall imports and find stronger evidence of foreign R&D spillovers than that reported by Coe and Helpman (1995).

An alternative method of capturing the effects of international technology diffusion is to use patent citation data. Sjöholm (1996) for example relates the citations of Swedish firms to patents owned by foreign inventors to a number of correlates including bilateral imports. The results suggest a positive correlation between patent citations and imports, a result consistent with imports contributing to international knowledge spillovers. Eaton and Kortum (1996) use information on where country's patent arguing that this is likely to convey information on where ideas are likely to be used. Relating bilateral patenting in OECD countries to a number of explanatory variables they find that imports are not a significant determinant of technology diffusion as measured by bilateral patenting.

6 Engelbrecht (1997a) tests the robustness of the results on the R&D spillover variable to the inclusion of a general human capital variable and a catch-up term. He finds that their inclusion reduces the coefficient on the R&D spillover variable by around 30%. Lichtenberg and van Pottelsberghe de la Potterie (1998) argue that there is an aggregation bias in the construction of the R&D spillover variable and propose an alternative that removes this bias. Results using this alternative still find trade to be an important channel of R&D spillovers.

3. Contingent international technology diffusion

The notion that countries may gain from access to each other's knowledge or technology is not new. More than a generation ago Gerschenkron (1962) discussed the so-called 'advantage of backwardness', whereby countries positioned inside the world technological frontier obtain a nonreciprocal benefit by learning from the technological leaders. Gerschenkron observed that 'Industrialisation always seemed the more promising the greater the backlog of technological innovations which the backward country could take over from the more advanced country' (1962, p. 8). One implication of this statement is that the further a country is behind the leader the greater the backlog of knowledge available for diffusion and so the larger the potential knowledge spillovers.

Abramowitz (1986) accepts that being backward carries the potential for rapid advance, and that this should imply convergence over long periods of time. But backwardness in itself is unlikely to lead to greater knowledge diffusion and catch-up, unless certain preconditions exist that allow countries to absorb the inflow of foreign ideas and knowledge. These preconditions have been termed 'social capability' or 'absorptive capacity'. Abramovitz has a broad concept in mind, and identifies a large number of factors that could be considered important for a country's absorptive capacity, making measurement difficult. More recently, Cinera and van Pottelsberghe de la Potterie (2001) argue that 'in order to gauge the importance of international spillover effects, it may also be worth it to examine the factors improving the absorptive capabilities of foreign R&D such as education, training, mobility of the human capital or R&D collaborations'.

Despite theoretical arguments suggesting that the ability of a country to absorb and assimilate foreign knowledge is likely to be an important determinant of the extent of foreign knowledge spillovers, to date there has been relatively little work addressing this issue. Studies that have been undertaken tend to concentrate on two variables often associated with the idea that a firm or country needs to have a certain type of skill in order to be able to successfully adopt foreign technology, namely human capital (Nelson and Phelps, 1966) and R&D expenditures (Cohen and Levinthal, 1989).

Nelson and Phelps (1966) argue that the rate of technology absorption depends on the technology gap between the leading country and the follower. In this spirit, Benhabib and Spiegel (1994) and Engelbrecht (1997b) include a human capital/productivity catch-up interaction term in regressions on the growth of either TFP or GDP, which also include a separate human capital variable to account for domestic innovation. Benhabib and Spiegel (1994) find that the interaction term is significant and has the expected sign only for developing countries, while the domestic innovation rate for these countries is negative but insignificant. The opposite result is found for the wealthiest third of countries. In contrast Engelbrecht (1997b) finds that both variables enter significantly and with the expected sign for OECD countries. When including this interaction term, Engelbrecht (2002) finds for a sample of developing countries results similar to Benhabib and Spiegel (1994), namely a negative but insignificant coefficient on the education variable and a positive and significant coefficient on the interaction term. Falvey et al. (2007) use threshold regression methods to examine whether human capital and the technology gap impact upon trade-related knowledge spillovers. They find that higher levels of human capital are associated with larger knowledge spillovers, while spillovers have the strongest impact on productivity in countries with an intermediate technology gap. The results suggest that human capital can play a role in the international diffusion of technology, but that its role in encouraging domestic innovation is limited to the most advanced countries.

Cohen and Levinthal (1989) argue that in order to acquire outside technology a firm may itself need to invest in R&D. These authors argue that own R&D expenditures are critical for enabling the firm to understand and evaluate new technological trends and innovations. Empirical evidence exists to support these claims. Griffith et al. (2004) use industry-level data from twelve OECD countries to study the main determinants of productivity dynamics and find that conditional on a certain productivity gap to the leader country, subsequent productivity growth in an industry is higher, the higher are its R&D expenditures. This is consistent with R&D playing a similar role to human capital in facilitating technology diffusion. Dougherty (1997) also presents evidence to suggest that technology diffusion is positively related to the presence of domestic enterprise-level R&D programmes using data on Chinese enterprises. Using the Coe and Helpman framework, Crespo-Cuaresma et al. (2004) find that the benefits of foreign R&D spillovers are stronger in OECD countries that conduct significant R&D and that have relatively high levels of absorptive capacity as measured by education variables.

A further aspect of absorptive capacity mentioned by Abramowitz has also been emphasised in the recent literature, namely institutional barriers to the adoption of new technology. In a series of papers, Parente and Prescott (1994, 1999 and 2003) argue that absorptive capacity is to a large extent determined by institutional aspects that give rise to these so called absorption barriers, which in turn lead to the inefficient use of inferior technologies. This argument is based on the fact that many of these barriers are assumed to be put in place to protect the interests of groups vested in current production processes. Intuitively, as long as firms are not threatened by the prospect that their competitors might introduce more productive technologies, they may prefer to stick to their current technology, although better ones are available. This view that barriers may prevent technology adoption and may delay economic development is not new. Rosenberg and Burdzell (1986) and Mokyr (1990) also argue that lower barriers to the adoption of technology help explain why modern economic growth began in the West rather than the East.

Parente and Prescott (1994) argue that although the global pool of knowledge is readily accessible by each country, not all countries employ the best available technologies, because implementing new technologies and work practices involves costs. These costs are to some extent determined by institutional constraints such as the regulatory environment and competition policy. In their model, firms have to invest in order to increase the quality of their plants. However, the amount of investment required to achieve a certain level of quality depends on the institutional environment and therefore differs across countries. They find that even small variations in the costs imposed by the institutional environment give rise to large differences in income levels. In a related paper, Parente and Prescott (1999) focus on monopoly rights as the main institutional feature that acts as a barrier to the adoption of foreign technologies. If industry insiders have monopoly rights to the current technology they will resist the adoption of better production techniques. The greater the strength of protection granted to the insiders, the greater the amount of resources that potential entrants with superior technology have to spend in order to enter the industry. Thus, more competitive economies are likely to benefit from spillovers to a larger extent.

While barriers protecting industry insiders are likely to be considerable, labour market institutions are likely to be a further relevant barrier to technology adoption. Labour unions are another group with vested interests that may potentially oppose the introduction of possibly labour-saving technologies and could also be considered to be a group with vested interests in limiting technology adoption.

Empirically, Crespo-Cuaresma et al. (2004) in their paper also consider whether indicators of product and labour market regulations impact upon the extent of foreign knowledge spillovers. Their results indicate that measures of product market regulation, employment protection and the coordination of wage bargaining all impact upon the extent of foreign knowledge spillovers. In all cases higher barriers are associated with lower foreign knowledge spillovers. Coe et al. (2009) also search for conditions enhancing the benefits of R&D spillovers, concentrating on the importance of institutions. They find that countries where it is easier to do business, with higher quality tertiary education, with higher levels of patent protection, and with English and German legal systems benefit to a greater extent from foreign knowledge spillovers.

4. Methodology

The starting point is a simple Cobb-Douglas production function of the form:

$$Y = AK^{\alpha}L^{1-\alpha}, \quad A > 0,\ 0 < \alpha < 1$$

which can be written in intensive form as:

$$y = Ak^{\alpha}$$

where $y = Y/L$ and $k = K/L$. Expressing this equation in logs and taking first differences gives[7]:

$$\Delta \ln y = \Delta \ln A + \alpha \Delta \ln k \quad (1)$$

which expresses the (approximate) growth rate of output per worker to the growth rate of technology and the growth rate of the capital-labour ratio. What remains is to specify a form for technological progress. Here the following is assumed:

$$\Delta \ln A = \gamma_1 \Delta \ln F \quad (2)$$

where F is the R&D stock available. In the analysis below the R&D stock available is split into a domestic and a foreign component. Combining equations (1) and (2) gives:

$$\Delta \ln y_{iht} = \gamma_1 \Delta \ln F_{iht} + \alpha \Delta \ln k_{iht}$$

where subscripts i, h and t refer to industry, country and time respectively. For purposes of estimation a number of modifications are made to this equation. In particular industry, country and time fixed effects are included, as is an error term and the initial logged value of output per worker to allow for conditional convergence. The basic estimating equation is therefore:

$$\Delta \ln y_{iht} = \gamma \Delta \ln F_{iht} + \beta_1 \Delta \ln k_{iht} + \beta_2 \ln y_{ih1995} + \alpha_i + \delta_h + \pi_t + \varepsilon_{iht} \quad (3)$$

The extent of knowledge flows from the donor countries and industries to the recipient countries and industries are captured following the approach of Nishioka and Ripoll (2012) by focusing on the concept of the R&D content of intermediates. Intermediate inputs are thus assumed as the channel through which knowledge is diffused.

Following Nishioka and Ripoll (2012) the intermediate input weighted R&D stocks are calculated in the following manner. Let g and $h = 1, \ldots, G$ be indexes for goods and i and $j = 1, \ldots, N$ for countries.

7 A major reason for focusing on this first-difference specification is that the levels of the variables included in the regression model tend to be non-stationary, while the first differences tend to be stationary. For more information on this see Appendix D.

Assume that every good is consumed either as a final good or as an intermediate input. Let Q_i be a $G \times G$ diagonal matrix for country i's gross output, and $B_{ji}(g,h)$ be the amount of intermediate input g from country j used to produce one unit of gross output of country i's good h. If $i = j$, $B_{ji}(g,h)$ is the typical (g,h) element of the $G \times G$ matrix of domestic intermediate requirements B_{ii}. If $i \neq j$, $B_{ji}(g,h)$ is the typical (g,h) element of the $G \times G$ matrix of foreign intermediate requirements B_{ji}. Based on these definitions, the following global matrixes can be defined:

$$Q = \begin{bmatrix} Q_1 & 0 & \cdots & 0 \\ 0 & Q_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & Q_N \end{bmatrix}$$

$$B = \begin{bmatrix} B_{11} & B_{12} & \cdots & B_{1N} \\ B_{21} & B_{22} & \cdots & B_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ B_{N1} & B_{N2} & \dots & B_{NN} \end{bmatrix}$$

where Q is an $NG \times NG$ diagonal matrix of gross output and B is an $NG \times NG$ matrix of global intermediate techniques whose typical element is $B_{ji}(g,h)$. It is then possible to distinguish between gross output (Q), net output or final demand ($Q - BQ$) or $(I - B)Q$, and intermediate demand for production (BQ). The term $(I - B)^{-1}Q$ represents total (direct and indirect inputs) needed to produce Q.

Let S_j be a $1 \times G$ row vector whose gth element is the business R&D stock used directly to produce good g in country j, and let D_j be a $1 \times G$ row vector whose gth element is the R&D stock per unit of good g. Then $D_j Q_j = S_j$ and we can define D to be a $1 \times NG$ global vector of direct R&D requirements,

$$D = [D_1, D_2, \dots, D_N]$$

and S to be a $1 \times NG$ global vector of domestic R&D stocks

$$S = [S_1, S_2, \dots, S_N]$$

where $S = DQ$

The R&D content of intermediates is defined as the total R&D stock embodied in intermediate inputs BQ. The total intermediate requirements needed to deliver BQ are given by $(I - B)^{-1}BQ$. The R&D content of intermediate inputs, F, is then defined as,

$$F = D(I - B)^{-1}BQ \tag{4}$$

with F being a $1 \times NG$ global vector of total R&D stock embodied in the production of intermediate inputs. A typical element F_{ih} from vector F corresponds to the measure of the domestic and foreign R&D embodied in the intermediate inputs sector h in country i purchases from all sectors and countries.

A measure including only the 'direct' R&D content of intermediates F^d is given by:

$$F^d = DBQ \tag{5}$$

Nishioka and Ripoll (2012) discuss further how these measures can be disaggregated along a number of dimensions. Initially they separate the total effects of R&D by industry, separating own industry intermediates from intermediates from other industries. The R&D stock embodied in intermediate goods industry h in country i buys from its own industry in all countries (including itself) in time t is defined as:

$$\sum_j D_{jt}(h)\, A_{jit}(h,h) Q_{it}(h) \tag{6}$$

where $A = (I - B)^{-1}B$ so that the R&D content of intermediates can be defined as $F = DAQ$. The R&D stock embodied in intermediate goods industry h in country i buys from all other industries in all countries is defined as:

$$\sum_j \sum_{g \neq h} D_{jt}(g)\, A_{jit}(g,h) Q_{it}(h) \tag{7}$$

Of more relevance however is a disaggregation that involves separating the effects of R&D content from domestic and foreign source countries, which are respectively given by the following two equations:

$$F_D = \sum_g D_{it}(g)\, A_{iit}(g,h) Q_{it}(h) \tag{8}$$

$$F_F = \sum_{j \neq i} \sum_g D_{jt}(g)\, A_{jit}(g,h) Q_{it}(h) \tag{9}$$

In the analysis below this latter disaggregation is introduced into the regression analysis.

5. Data and descriptive analysis

5.1. R&D STOCKS

Data on R&D expenditure are obtained from the OECD ANBERD database. The OECD uses the implicit GDP deflator and PPP conversions to compute real R&D expenditures.[8] These deflators provide an approximate measure of the average real opportunity cost of carrying out R&D. The ANBERD dataset provides industry level R&D data according to the ISIC revision 3.1 classification. To increase the number of available countries in the dataset some industries as available from the WIOD have to be combined which results in a set of R&D data for ten manufacturing industries as listed in Appendix Table C.1. After imputing a small number of values we are left with R&D data for these industries for 20 countries[9]: Australia, Belgium, Canada, Czech Republic, Germany, Spain, France, United Kingdom, Greece, Hungary, Ireland, Italy, Japan, Netherlands, Poland, Portugal, Singapore, Slovenia, Turkey and the USA. We will thus examine knowledge spillovers from these manufacturing industries and countries. For the remaining countries and industries we have to follow the approach of Coe et al. (1997) and assume that the R&D stocks are zero. While not an ideal solution, given the high degree of concentration of R&D in a small number of developed countries and in a small number of manufacturing industries within these countries this assumption is unlikely to affect the results drastically.

Using data on R&D expenditures the domestic R&D stock for industry g in country j in time t is computed using the perpetual inventory method according to the following equation:

$$S_{gjt} = (1 - \delta)S_{gj,t-1} + R_{gjt}$$

where δ is the depreciation rate of knowledge obsolescence (set at 15%) and R_{gjt} is real business R&D expenditure. The initial value of the real business R&D stock is calculated according to the following equation:

$$S_{gj0} = \frac{R_{gj0}}{\delta + \pi_{gj}}$$

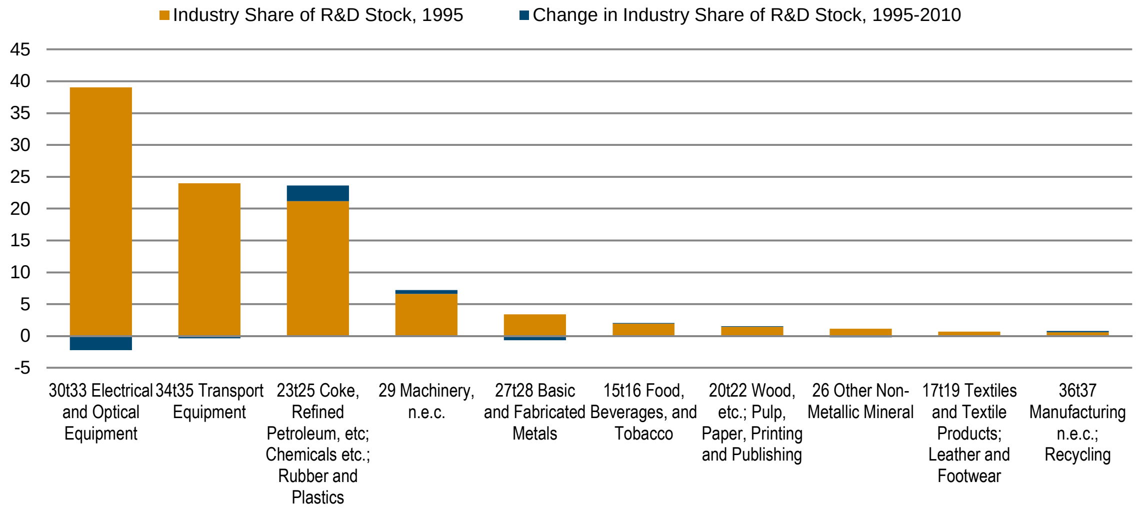
where π_{gj} is the average growth rate of real business R&D expenditures for industry g in country j over the whole period for which data are available. In general, the initial year in our dataset is 1994, which allows us to maximise the number of industries and countries used in the analysis.

Figure 1 reports the shares of R&D stocks by industry in 1995 and the change between 1995 and 2010. As expected the R&D stocks of electrical and optical equipment, transport equipment and chemicals and chemical products make up the vast majority – over 80% – of the total R&D stock, with little change in this share over time. The shares of R&D stocks in the remaining industries are relatively low, and indicate the extent to which R&D is concentrated in a small number of industries.

8 Specifically, OECD reports R&D expenditure in 2000 prices and 2000 PPP dollars.

9 Around 10% of observations had to be imputed due to missing values for particular years. Where data was not available we used linear interpolation to fill in the missing numbers.

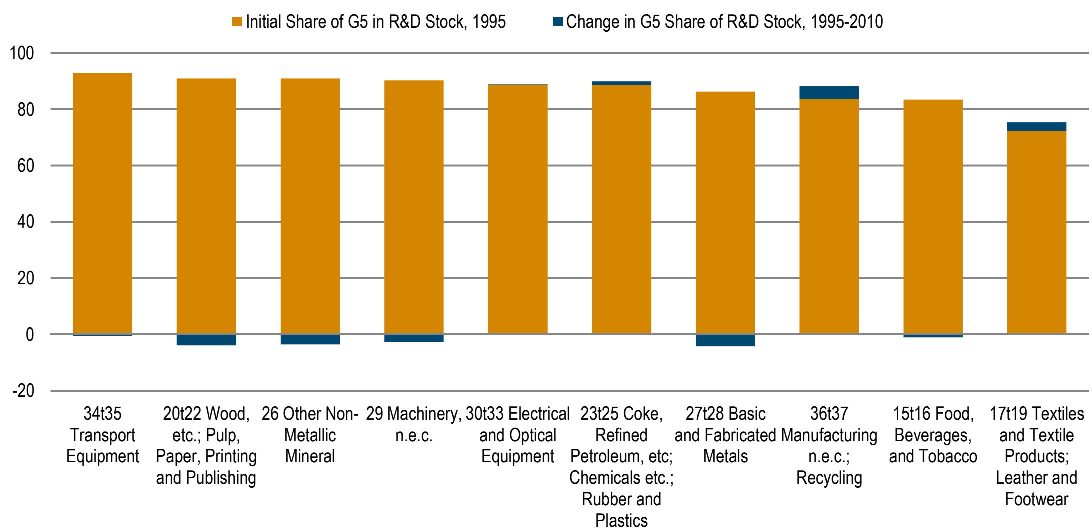
Figure 1 / Industry shares of domestic R&D stocks, in %



Source: OECD ANBERD Database; wiiw calculations.

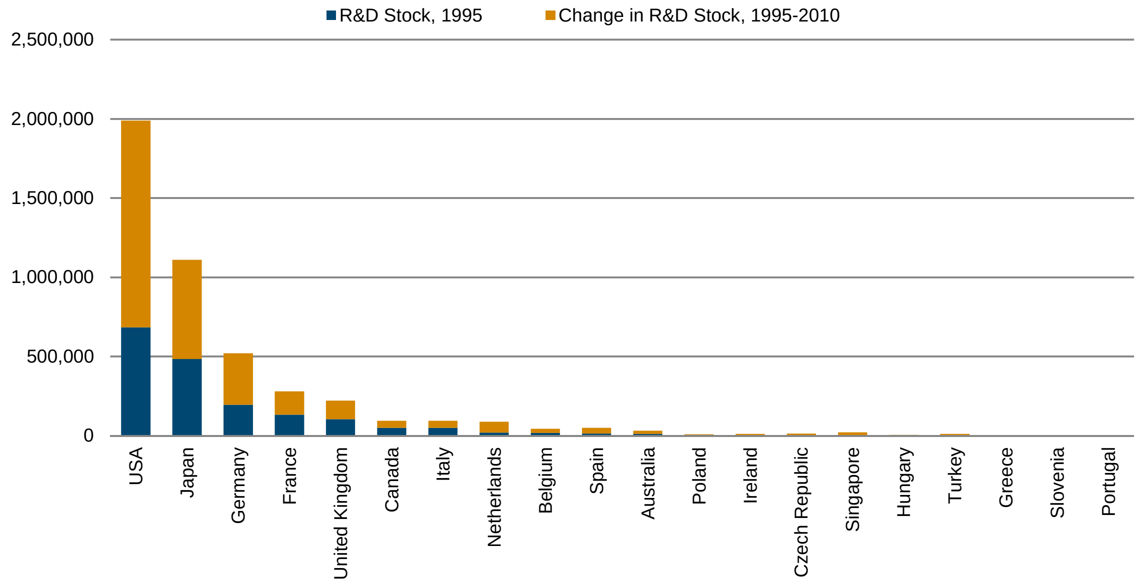
Figure 2 reports shares of G5 countries in the R&D stocks by industry. The figure indicates that these shares are very large and also tend to be above 80%, indicating the extent to which R&D is concentrated in a small number of countries. This can be further seen in Figure 3, which shows the values of the R&D stocks in 1995 and the change between 1995 and 2010 by country. The figure clearly shows that the USA and Japan dominate the R&D stocks of our sample of countries, with Germany, France and the UK also showing relatively high R&D stocks. Figure 4 reports similar information by industry, and here we again see the extent to which R&D is concentrated in electrical and optical equipment, transport equipment and chemicals and chemical products. We also observe that it is in these three industries that the R&D stocks have increased most rapidly, with relatively large increases also observed in machinery, nec (29).

Figure 2 / Shares of G5 countries in domestic R&D stocks by industry, in %



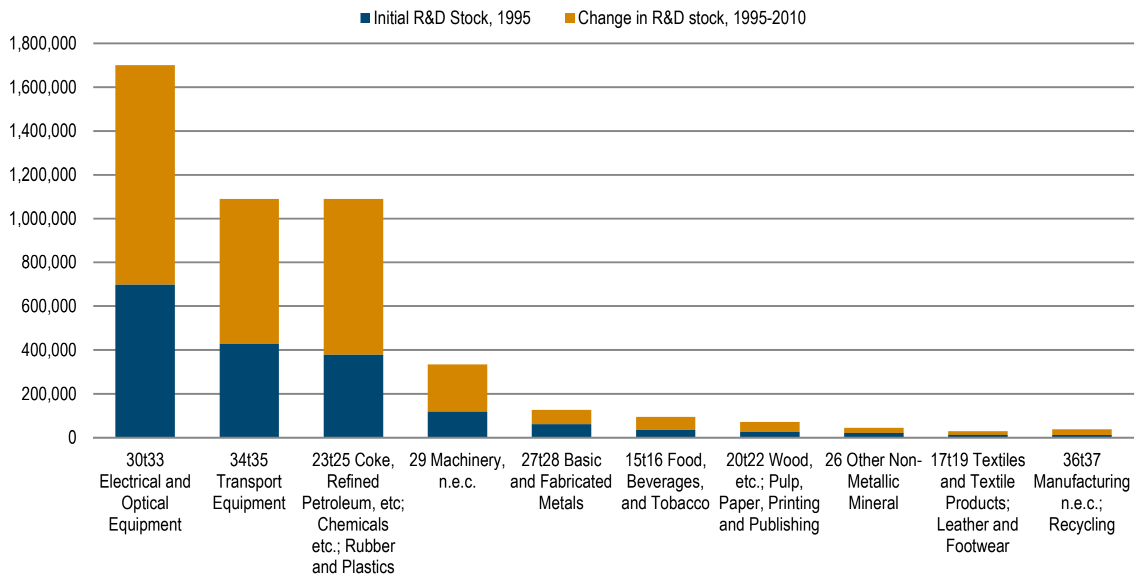
Source: OECD ANBERD Database; wiiw calculations.

Figure 3 / Initial R&D stocks by country and changes between 1995 and 2010, in million USD



Source: OECD ANBERD Database; wiiw calculations.

Figure 4 / Initial R&D stocks by industry and changes between 1995 and 2010, in million USD



Source: OECD ANBERD Database; wiiw calculations.

5.2. R&D STOCKS OF INTERMEDIATE INPUTS

Information on intermediate flows required for the calculation of the R&D stock of intermediates are taken from the recently compiled World Input-Output Database (WIOD), which reports data on socio-economic accounts, international input-output tables and bilateral trade data across 35 industries and 40 countries over the period 1995-2009.[10] These data result from an effort to bring together information from national accounts statistics, supply and use tables, data on trade in goods and services and corresponding data on factors of production (capital and labour by educational attainment categories). The starting point for the WIOD data are national supply and use tables (SUTs) which have been collected, harmonised and standardised for 40 countries (the 27 EU countries, Australia, Brazil, Canada, China, India, Indonesia, Japan, Korea, Mexico, Russia, Taiwan, Turkey and the US) over the period 1995-2009. These tables contain information on the supply and use of 59 products in 35 industries together with information on final use (consumption, investment) by product, value added and gross output by industry. These tables have further been benchmarked to time series of national accounts data on value added and gross output to allow for consistency over time and across countries. This approach allows one to provide information on the supply and use of a product by industry for each country. Using detailed trade data the use tables are then split up into domestic and imported sourcing components, with the latter further split by country of origin. Data on goods trade were collected from the UN COMTRADE database at the HS 6-digit level. These detailed bilateral trade data allow one to differentiate imports by use categories (intermediates, consumption and investment goods) by applying a modified categorisation based on broad end-use categories at the product classification. Bilateral trade in services data were collected from various sources. Services trade data are only available from Balance of Payments (BoP) statistics providing information at a detailed level only in BoP categories. Using a correspondence these data were merged to the product level data provided in the supply and use tables. The differentiation into use categories of services imports was based on information from existing import use or import input-output tables. Combining this information from the bilateral trade data by product and use categories with the supply and use tables resulted in a set of 40 international use tables for each year. This set of international supply and use tables was then transformed into an international input-output table using standard procedures (model D in the Eurostat manual (Eurostat, 2008)). A rest-of-the-world was also estimated using available statistics from the UN and included in this table to account for world trade and production. This results in a world input-output database for 41 countries (including the rest-of-the-world) and 35 industries (for a detailed presentation of the database see Timmer, 2012).

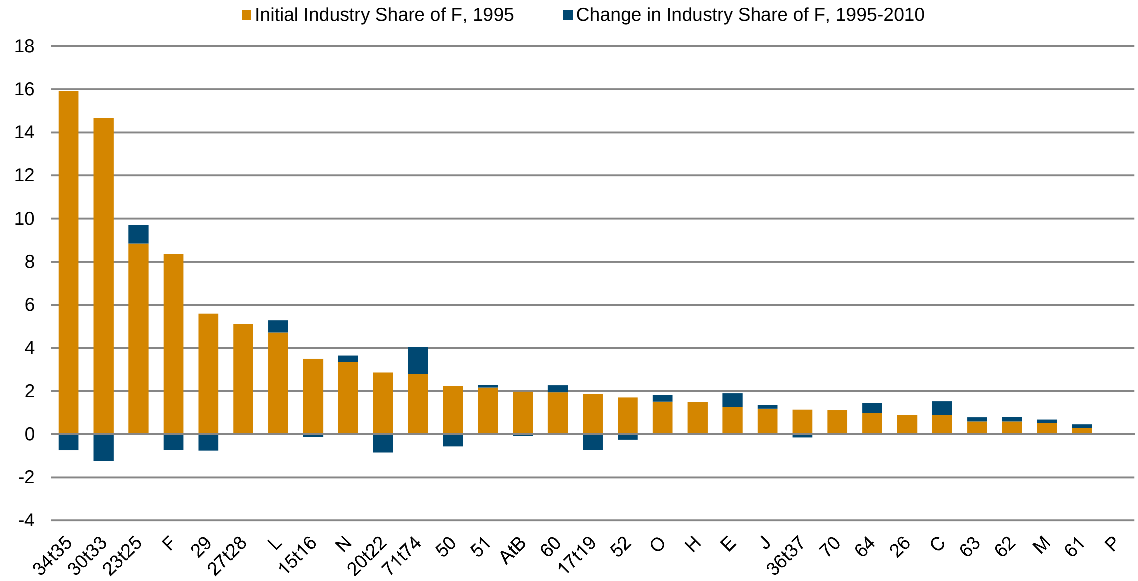
The variables capturing the R&D content of intermediate inputs, F, as defined in equation (4) and the ‘direct’ R&D content of intermediates, F^d, as defined in equation (5), can be constructed for each year between 1995 and 2010 for all 40 countries included in the WIOD using R&D data for the 10 manufacturing industries as described above. Due to inter-industry linkages one therefore ends up with direct and indirect R&D expenditures for all sectors as listed in Appendix Table C.1. As mentioned above, for the industries and for countries for which we do not have R&D stock data we set the values of the R&D stock equal to zero when calculating F and F^d.

Figure 5 reports the industry shares of F in 1995 and the change between 1995 and 2010. As would be expected those industries for which we have R&D data tend to have the highest shares, and in particular industries 23t25, 30t33 and 34t35, which also dominate R&D expenditures (see Figure 1). Relatively

[10] Some of the associated data have been updated to 2011.

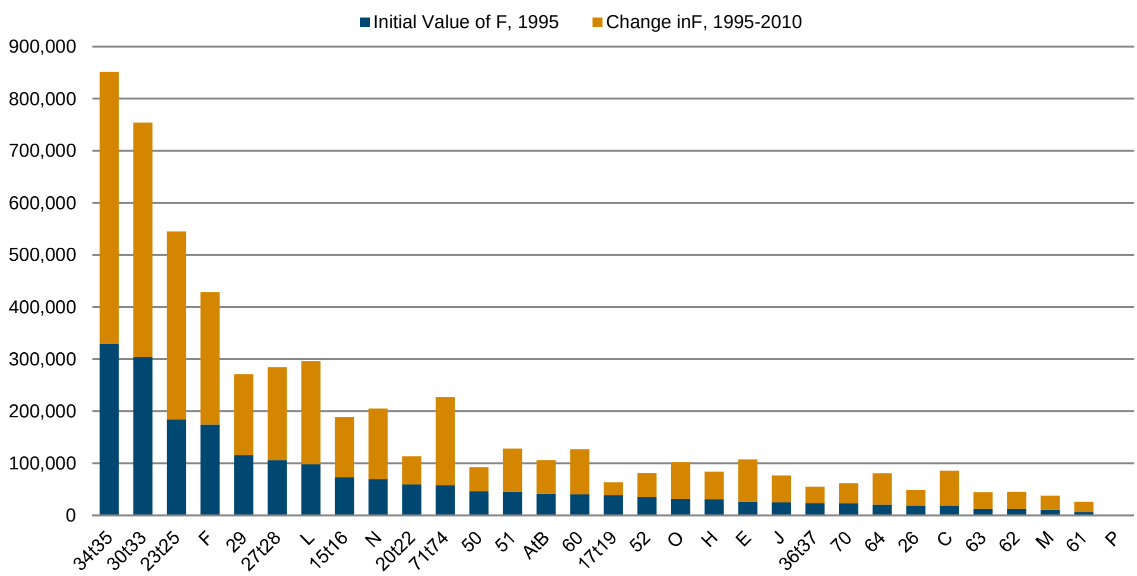
large shares are also found for Construction, suggesting that there are strong linkages between manufacturing and this sector. These figures are mirrored in Figure 6, which reports the initial value of F by industry and its change to 2010.

Figure 5 / Industry share of the R&D content of intermediate inputs F, in %



Source: OECD ANBERD and WIOD Data; wiiw calculations.

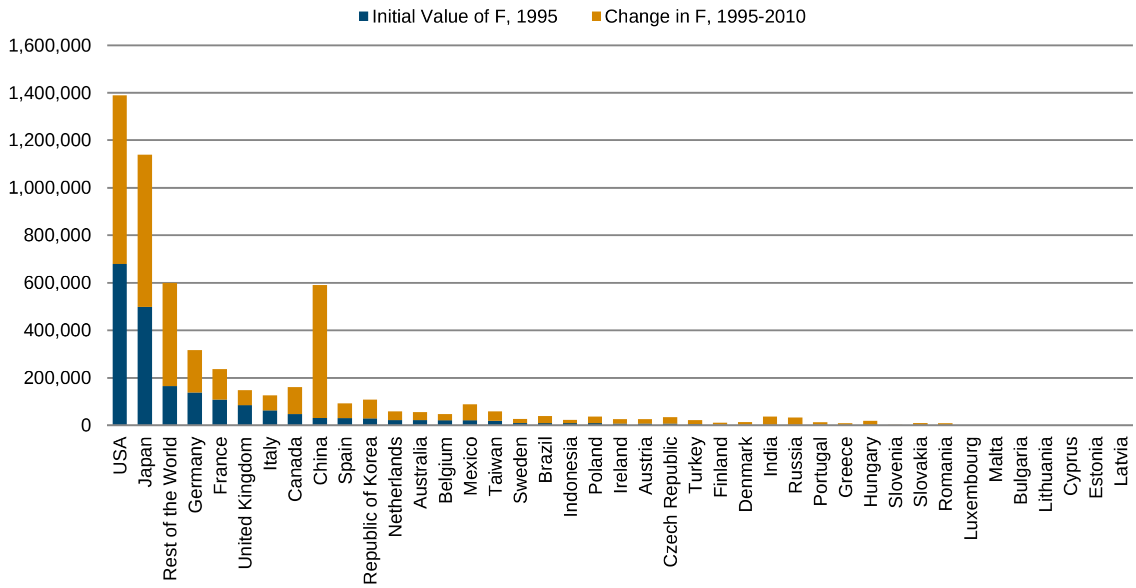
Figure 6 / Initial value of the R&D content of intermediate inputs, F, by industry and changes between 1995 and 2010, in USD



Source: OECD ANBERD and WIOD Data; wiiw calculations.

Figure 7 reports the initial value of F by country and its change between 1995 and 2010. Here we observe that the initial values of F were particularly high in the USA and Japan, and to a lesser extent Germany, France, the UK and the rest of the world, consistent with Figure 3 above. While large increases in the value of F were reported for the USA, Japan and the rest of the world between 1995 and 2010, the most striking aspect of this figure is the large increase in the value of F for China in 2010. This increase is solely due to increased flows of R&D-intensive intermediates into China over this period (since a lack of industry data for China means that we have to exclude it from the list of R&D source countries).

Figure 7 / Initial value of R&D content of intermediate inputs F by country and changes between 1995 and 2010, in million USD



Source: OECD ANBERD and WIOD Data; wiiw calculations.

5.3. ABSORPTIVE CAPACITY AND ABSORPTION BARRIERS

Finally, we require information on a number of additional variables that capture absorptive capacity and absorption barriers. Here we make use of a number of data sources. Initially we are interested in measures of absorptive capacity, and so use information from the Barro and Lee dataset on the average years of secondary schooling in the population over 15.[11] We further follow the approach of Cohen and Levinthal (1989) and use the logged value of R&D (ln*R&D*) from the ANBERD dataset as an additional indicator of absorptive capacity. In this case we set R&D equal to a small number (USD 1,000) where data are not available, which then allows us to calculate the logged values.

11 See http://www.barrolee.com/. This data has been used as a measure of absorptive capacity in similar studies (see for example Falvey et al., 2007).

Our second set of variables concentrates on indicators of absorption barriers (further details on the construction of these variables are found in Appendix A). In particular, we use the following variables that indicate the strength of labour market regulations from the OECD:

› Indicator for dismissal of employees on regular contracts (*EPR*)
› Indicator for strictness of regulations on temporary employment (*EPT*)
› Indicator for additional regulation of collective dismissal (*EPC*)

These variables are on a scale of 0 to 6, with 0 having the least and 6 the most restrictions. To be consistent with the hypotheses of Parente and Prescott (1994, 1999) we would require that R&D spillovers are weaker in countries with higher values of these indices.

To examine whether R&D spillovers are affected by the power of labour unions (*Union*) in limiting the take-up of potentially labour-saving technology we further use information on trade union density from the OECD.

A further indicator that we employ is the OECD indicator of product market regulation (*PMR*). The indicator represents the stringency of regulatory policy on a scale from 0 to 6 with higher numbers being associated with policies that are more restrictive to competition.[12] The data are available at the country level only and for three years (i.e. 1998, 2003, 2008). We fill in the missing years using linear interpolation.

A further variable that we include is an indicator of the strength of Intellectual Property Rights (*IPR*). IPRs are a policy tool aimed at encouraging innovative activities. By preventing the copying and imitation of a patent however, IPRs may reduce technology diffusion. Alternatively, since the information in patents is made public, stronger IPRS may encourage technology diffusion (see Breitwieser and Foster (2012) for a thorough discussion of the impacts of IPRs on innovation, technology diffusion and growth). The index of IPRs we use is that developed by Ginarte and Park (1997) and updated by Park (2008). The index uses information on the coverage of patents, membership in international treaties, enforcement mechanisms, restrictions on patent rights and duration. The index takes on a value between zero and five, with higher numbers indicating stronger protection.

Finally, we use information from the Heritage Foundation's Index of Economic Freedom as additional variables. In particular, we use the sub-indices on investment freedom (*invest*) and financial freedom (*finance*). Further details on the construction of these variables are relegated to Appendix B. The raw data are on a scale of zero to 100, with 100 implying no restrictions. To be consistent with the other measures of absorption barriers, we redefine this variable to be equal to $100 - freedom\ variable$, such that higher numbers imply more restrictions.

12 For further details see Wölfl et al. (2009).

6. Results

6.1. LINEAR RESULTS

Table 1 reports results from estimating the linear model described by equation (3), including various different fixed effects. The results are fairly consistent across specifications. We tend to find the familiar negative and significant coefficient on initial output per worker, indicating conditional convergence. The coefficients on the capital-labour ratio are positive and significant coefficient in all specifications, indicating that greater capital intensity is associated with higher labour productivity growth. In terms of the R&D variables we obtain coefficients that are consistently positive and significant. The coefficients on the two R&D variables are similar, though the coefficient is larger in the case of the total R&D content of intermediates (F) than that on the direct R&D content only (F^d). Coefficients on the R&D variables also tend to fall somewhat as we include additional fixed effects.[13] The coefficient estimates indicate that a 1% increase in the growth of the total R&D content of intermediates is associated with a higher growth rate of labour productivity of between 0.15% and 0.19%, with a similar increase for the direct R&D content of intermediates found to be associated with a 0.08 to 0.10 percentage higher growth rate of labour productivity. Such results are not insubstantial and are consistent with results found elsewhere in the literature (see for example Falvey et al., 2007; Crespo-Cuaresma et al., 2008).

Table 1 / Linear results I

	(1) $\Delta \ln y$	(2) $\Delta \ln y$	(3) $\Delta \ln y$	(4) $\Delta \ln y$	(5) $\Delta \ln y$	(6) $\Delta \ln y$
$\ln y_{1995}$	-0.0104***	-0.0106***	-0.0142***	-0.0110***	-0.0113***	-0.0143***
	(0.000742)	(0.000795)	(0.00289)	(0.000771)	(0.000815)	(0.00291)
$\Delta \ln k$	0.483***	0.423***	0.465***	0.488***	0.430***	0.474***
	(0.0278)	(0.0301)	(0.0333)	(0.0282)	(0.0305)	(0.0337)
$\Delta \ln F$	0.193***	0.180***	0.154***			
	(0.0188)	(0.0198)	(0.0209)			
$\Delta \ln F^d$				0.101***	0.0943***	0.0777***
				(0.0137)	(0.0142)	(0.0144)
Time F.E.	No	Yes	Yes	No	Yes	Yes
Country F.E.	No	No	Yes	No	No	Yes
Industry F.E.	No	No	Yes	No	No	Yes
Observations	15,850	15,850	15,850	15,850	15,850	15,850
R-squared	0.372	0.419	0.455	0.351	0.403	0.444
F-stat	285.0***	338.2***	87.10***	267.8***	330.2***	86.35***

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

While the above results suggest that the R&D stock of intermediates is positively associated with output per worker growth, our major interest in this report is to consider the impact of foreign R&D on labour productivity. As such, we would like to split up the total R&D stock into a domestic and foreign

13 The time, country and industry fixed effects are jointly significant.

component as in equations (8) and (9). Here we encounter a problem because the domestic R&D stock is not defined for a number of countries and a number of industries, meaning that we cannot calculate the log of the domestic R&D stock. To get around this problem we adopt two approaches. Firstly, we add a relatively small number (USD 100,000) to the domestic R&D stocks of those countries and industries for which data are not available. This allows us to calculate the log of the domestic R&D stocks. While this assumption implies that the change in the log of the domestic R&D stocks will be zero for such observations, it does allow us to include the full sample of observations. Secondly, we follow the approach adopted by Coe et al. (1997) and focus on the foreign R&D stocks only. The results when including the domestic stock of R&D are reported in Table 2. Results on the additional control variables are largely similar to those reported in the previous table, while the coefficients on the change in the domestic R&D stock are generally insignificant and often negative. This is likely to reflect the fact that we impute a large number of observations for this variable, with the lack of variation in the resulting growth rates making insignificant coefficients likely. Coefficients on the foreign R&D stock are, however, consistently positive and significant, with the size of the coefficients being very similar to those for the total R&D stock reported in the previous table.

Table 2 / Linear results II

	(1)	(2)	(3)	(4)	(5)	(6)
	$\Delta \ln y$	$\Delta \ln y$	$\Delta \ln y$	$\Delta \ln y$	$\Delta \ln y$	$\Delta \ln y$
$\ln y_{1995}$	-0.0102***	-0.0105***	-0.0142***	-0.0109***	-0.0113***	-0.0143***
	(0.000764)	(0.000829)	(0.00289)	(0.000787)	(0.000838)	(0.00291)
$\Delta \ln k$	0.481***	0.422***	0.465***	0.488***	0.430***	0.474***
	(0.0279)	(0.0303)	(0.0335)	(0.0283)	(0.0306)	(0.0337)
$\Delta \ln F_D$	-0.0334**	-0.0143	-0.0119			
	(0.0142)	(0.0145)	(0.0150)			
$\Delta \ln F_F$	0.193***	0.178***	0.152***			
	(0.0185)	(0.0199)	(0.0212)			
$\Delta \ln F_D^d$				-0.0185	-0.00411	-6.50e-05
				(0.0122)	(0.0120)	(0.0120)
$\Delta \ln F_F^d$				0.0962***	0.0875***	0.0725***
				(0.0128)	(0.0136)	(0.0137)
Time F.E.	No	Yes	Yes	No	Yes	Yes
Country F.E.	No	No	Yes	No	No	Yes
Industry F.E.	No	No	Yes	No	No	Yes
Observations	15,850	15,850	15,850	15,850	15,850	15,850
R-squared	0.373	0.419	0.455	0.351	0.402	0.443
F-stat	220.8***	318.4***	86.17***	205.1***	310.9***	85.52***

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 3 reports results when we drop the domestic R&D stock, including the foreign stock only. The results are very similar to those found when including the domestic stocks, which suggests that the inclusion of our measure of the domestic stocks doesn't affect the results on the foreign stock a great deal. For this reason, we now focus on results when just including the foreign R&D stock. For reasons of brevity, we further concentrate on results when including time, country and industry fixed effects, and on those results when we use the total (foreign) R&D content of intermediate inputs rather than the direct effect only.

Table 3 / Linear results III

	(1)	(2)	(3)	(4)	(5)	(6)
	$\Delta \ln y$	$\Delta \ln y$	$\Delta \ln y$	$\Delta \ln y$	$\Delta \ln y$	$\Delta \ln y$
$\ln y_{1995}$	-0.0104***	-0.0106***	-0.0142***	-0.0110***	-0.0113***	-0.0143***
	(0.000741)	(0.000797)	(0.00289)	(0.000770)	(0.000816)	(0.00291)
$\Delta \ln k$	0.482***	0.422***	0.465***	0.488***	0.430***	0.474***
	(0.0278)	(0.0301)	(0.0334)	(0.0282)	(0.0305)	(0.0336)
$\Delta \ln F_F$	0.190***	0.176***	0.150***			
	(0.0180)	(0.0192)	(0.0202)			
$\Delta \ln F_F^d$				0.0940***	0.0870***	0.0725***
				(0.0123)	(0.0130)	(0.0131)
Time F.E.	No	Yes	Yes	No	Yes	Yes
Country F.E.	No	No	Yes	No	No	Yes
Industry F.E.	No	No	Yes	No	No	Yes
Observations	15,850	15,850	15,850	15,850	15,850	15,850
R-squared	0.372	0.419	0.455	0.351	0.402	0.443
F-stat	289.2***	338.2***	87.04***	270.0***	330.3***	86.44***

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 4 introduces our indicators of absorptive capacity and absorption barriers linearly into the model. We include each of these variables separately in our model to avoid issues of multicollinearity and then in the final column include them all together. The results indicate that the initial output per worker term remains negative when including these additional variables (though the coefficient is often not significant), while coefficients on the capital-labour ratio remain positive and significant. The coefficients on the foreign R&D stock variable remain positive, and are usually significant. The coefficient on this variable tends to fall when the sample size is reduced (due to missing values on one of the institutional variables) however. Turning to the coefficients on the institutional variables themselves, we find a number of interesting results. The coefficients on the measures of human capital and the log of R&D expenditure are positive but insignificant.[14] The indicators of labour market regulation have a consistently negative and significant coefficient, suggesting that higher labour market regulations are associated with lower output per worker growth. Similar results are found for the index of IPR protection and the measure of investment freedom. For the remaining variables we find no significant coefficient, except in the case of financial freedom where less freedom is associated with higher growth. When including all institutional variables together all indicators with the exception of PMR and finance remain significant. Additionally the coefficient on product market regulation now also becomes negative and significant.

[14] In the case of R&D expenditure, this may again be due to the fact that the level of R&D expenditure is missing for a large number of observations, with the missing observations being replaced by USD 1,000. The lack of variation in this variable for such observations may lead to an insignificant coefficient on the variable. Many previous studies have found either an insignificant or even negative coefficient on indicators of schooling in growth regressions (e.g. Pritchett, 2001).

Table 4 / Linear results IV

VARIABLES	(1) $\Delta \ln y$	(2) $\Delta \ln y$	(3) $\Delta \ln y$	(4) $\Delta \ln y$	(5) $\Delta \ln y$	(6) $\Delta \ln y$	(7) $\Delta \ln y$	(8) $\Delta \ln y$	(9) $\Delta \ln y$	(10) $\Delta \ln y$	(11) $\Delta \ln y$
$\ln y_{1995}$	-0.0142***	-0.0142***	-0.00500	-0.00497	-0.00422	-0.00486	-0.00404	-0.0134***	-0.0142***	-0.0143***	-0.00263
	(0.00289)	(0.00289)	(0.00409)	(0.00409)	(0.00454)	(0.00394)	(0.00396)	(0.00301)	(0.00289)	(0.00288)	(0.00508)
$\Delta \ln k$	0.465***	0.465***	0.629***	0.632***	0.673***	0.636***	0.622***	0.472***	0.466***	0.461***	0.690***
	(0.0335)	(0.0334)	(0.107)	(0.107)	(0.134)	(0.0955)	(0.103)	(0.0357)	(0.0336)	(0.0338)	(0.148)
$\Delta \ln F_F$	0.150***	0.150***	0.0806***	0.0778***	0.0635*	0.0894***	0.0749**	0.144***	0.150***	0.148***	0.0576
	(0.0202)	(0.0202)	(0.0287)	(0.0290)	(0.0348)	(0.0228)	(0.0336)	(0.0227)	(0.0203)	(0.0201)	(0.0371)
Syr	0.00650										0.00764
	(0.00636)										(0.00764)
$\ln \mathrm{R\&}D$		0.000223									-0.000371
		(0.000319)									(0.000513)
EPR			-0.0246**								-0.0233
			(0.00983)								(0.0244)
EPT				-0.0190***							-0.0165**
				(0.00416)							(0.00676)
EPC					-0.0841***						-0.0979**
					(0.0308)						(0.0454)
Union						0.000170					-0.000234
						(0.00109)					(0.00165)
PMR							0.0146				-0.0202**
							(0.0112)				(0.0103)
IPR								-0.00950**			-0.0303**
								(0.00419)			(0.0123)
Invest									-0.000327**		-0.00109***
									(0.000166)		(0.000294)
Finance										0.000777***	0.000257
										(0.000171)	(0.000232)
Observations	15,850	15,850	9,559	9,559	8,061	10,372	9,742	14,200	15,850	15,850	7,374
R-squared	0.455	0.455	0.445	0.446	0.468	0.456	0.471	0.455	0.455	0.456	0.476
F-stat	86.41***	86.05***	92.94***	94.22***	94.07***	108.8***	100.9***	82.53***	86.39***	95.54***	93.68***

Notes: Robust standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1; All models include unreported time, industry and country fixed effects.

6.2. FOREIGN R&D AND ABSORPTIVE CAPACITY

In this section, we examine whether the relationship between the foreign R&D stock of intermediates and labour productivity is affected by the indicators of absorptive capacity and absorption barriers described above. Our econometric strategy involves estimating a model of the following form:

$$\Delta \ln y_{iht} = \gamma_1 \Delta \ln F_{F,iht} 1(Z_{iht} \leq \lambda) + \gamma_2 \Delta \ln F_{F,iht}\, 1(Z_{iht} > \lambda) + \beta_1 \Delta \ln k_{iht} + \beta_2 \ln y_{ih1995} + \beta_2 Z_{iht} + \alpha_i + \delta_h + \pi_t + \varepsilon_{iht}$$

Here Z is our indicator of absorptive capacity or absorption barriers and 1 is the indicator function taking the value one if the term in brackets is true. The model differs from a standard linear model in that the elasticity of labour productivity with respect to foreign R&D (i.e. γ) is allowed to differ depending upon whether absorptive capacity is above or below some threshold value (λ). In particular, the elasticity of labour productivity is given by γ_1 if absorptive capacity is below (or equal to) the threshold and is given by γ_2 if absorptive capacity is above the threshold. The actual threshold value is calculated endogenously and more details on how this is obtained can be found in Appendix B.[15] When estimating this model we further include the threshold variable, Z, linearly. To the set of threshold variables capturing absorptive capacity and absorption barriers we also include the initial logged value of labour productivity ($\ln y_{1995}$). Doing this, allows us to examine whether an indicator of relative backwardness impacts upon the relationship between foreign R&D and labour productivity.[16] While being further behind the technological leader means that there is more technology and knowledge to borrow and assimilate, it may also mean that a country or sector doesn't have the ability to make use and benefit from advanced technology (see Falvey et al., 2007). As such, the impact of backwardness measures on the relationship between foreign R&D and labour productivity growth is ambiguous from a theoretical point of view.

Results from estimating a single threshold are presented in Table 7. Coefficients on initial output per worker and the growth of the capital-labour ratio are consistent with results above, with coefficients generally being significantly negative and significantly positive respectively. Before turning to the coefficients on the growth of the foreign R&D stock, it is worth mentioning that in 10 out of the 11 cases we find evidence of a significant threshold (the exception being when the log of R&D is the threshold variable). This implies that the threshold model is preferred to the linear model, or in other words, that there are significant differences in the coefficients in the two regimes.

In terms of the threshold results, we get a variety of outcomes. In the case of the backwardness measure we find that the lower the labour productivity, the larger are the spillover effects. The coefficient in the low regime (0.264) is more than double that in the high regime (0.105) – though both are

15 The use of the threshold model rather than interaction terms has a number of advantages. Firstly, using threshold models doesn't impose a monotonic change in the effect of the explanatory variable as the threshold or interaction term increases (i.e. the impact of the explanatory variable on the dependent variable can switch signs and change size at different points on the distribution of the threshold variable). Secondly, the coefficients are easier to interpret. The impact of the explanatory variable on the dependent variable is given by a fixed parameter for all observations within a particular regime. With interaction terms it is more difficult to identify the overall impact of a change in the explanatory variable, with researchers often resorting to graphing the relationship for different values of the threshold/interaction variable. Thirdly, when the threshold/interaction variables are bound as in our case (e.g. between zero and six) the threshold model is less open to misinterpretation (e.g. extrapolating beyond the range of the threshold/interaction variable).

16 Falvey et al. (2007) present some evidence indicating that the impact of foreign R&D on labour productivity differs according to the degree of relative backwardness.

significant – indicating that foreign R&D spillovers appear to be significantly stronger in countries and industries that are further away from the frontier.

Turning to the indicators of absorptive capacity (i.e. *Syr* and ln*R&D*) we find consistent results. The coefficients indicate that foreign R&D spillovers are larger in countries with a higher number of average years of secondary schooling and in countries and industries that are more R&D-intensive. While the difference in coefficients (0.11 versus 0.27) in the case of *Syr* is significant, the differences in the case of ln*R&D* (0.15 versus 0.17) are not significant, i.e. the linear model is preferred.

Considering the case when labour market indicators are our threshold variable we find differences depending upon the indicator used. When using indicators of the strength of regulation on regular contracts and collective dismissal, we find that spillover effects are larger in the low regime (i.e. in countries with lower regulations). The coefficients in the high regimes tend to be quite small, with those in the low regime larger and statistically significant. The coefficient estimates imply that a 1% increase in the growth of the foreign R&D stock has a 0.13% increase in labour productivity growth for countries with a value of the *EPR* below the threshold and a -0.001% decrease for countries above the threshold. A similar change increases labour productivity growth by 0.21% for countries with *EPC* below the threshold, and by just 0.04% for countries above the threshold.

When considering the strength of regulation on temporary contracts we find the reverse. In particular, we find that while a 1% increase in the growth of the foreign R&D stock is associated with an increase in labour productivity of 0.24% for countries with EPT above the threshold, the change for countries below the threshold is just 0.03%. Finally, when using union density as our threshold variable we find that foreign R&D spillovers are larger in the low union density regime. A 1% increase in the growth of foreign R&D is associated with a 0.19% increase in labour productivity growth in the low regime, and a 0.03% increase in the high regime.

In terms of the remaining indicators, we find that in the cases of PMR, Invest and Finance the relationship between foreign R&D growth and labour productivity growth is stronger in the high regime, that is, in the regime with more stringent product market, investment and financial regulation. In the case of PMR the coefficient in the low regime is actually negative and significant. For Invest the difference in the coefficients on the foreign R&D variable between the two regimes is relatively small – though still significantly so (0.149 versus 0.172), while for Finance the differences are much larger (0.08 versus 0.237). Though this might be an unexpected result one should notice that these indicators could also reflect institutional quality in a broader sense. Thus, countries with higher institutional quality might attract more R&D-intensive firms or have tighter co-operations in R&D activities, etc. which would be possible explanations of that finding.

Table 5 / Single threshold results

	(1)	-2	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	$\ln y_{1995}$	Syr	$\ln R\&D$	EPR	EPT	EPC	Union	PMR	IPR	Invest	Finance
$\ln y_{1995}$	-0.011***	-0.014***	-0.014***	-0.00488	-0.00430	-0.00452	-0.00488	-0.00428	-0.013***	-0.0143***	-0.0142***
	(0.00226)	(0.00225)	(0.00226)	(0.00305)	(0.00304)	(0.00325)	(0.00300)	(0.00292)	(0.00234)	(0.00226)	(0.00224)
$\Delta\ln k$	0.457***	0.465***	0.465***	0.629***	0.632***	0.664***	0.631***	0.621***	0.467***	0.465***	0.454***
	(0.00587)	(0.00586)	(0.00587)	(0.0104)	(0.0104)	(0.0115)	(0.00993)	(0.00999)	(0.00611)	(0.00589)	(0.00588)
$\Delta\ln F_F^{LOW}$	0.264***	0.111***	0.149***	0.126***	0.0307***	0.208***	0.191***	-0.0291**	0.211***	0.139***	0.0807***
	(0.0107)	(0.00766)	(0.00631)	(0.0110)	(0.00999)	(0.0239)	(0.0129)	(0.0121)	(0.00759)	(0.00732)	(0.00792)
$\Delta\ln F_F^{HIGH}$	0.105***	0.212***	0.174***	-0.000967	0.241***	0.0357***	0.0339***	0.156***	-0.057***	0.172***	0.237***
	(0.00705)	(0.00952)	(0.0226)	(0.0145)	(0.0182)	(0.0104)	(0.00963)	(0.0108)	(0.0127)	(0.0103)	(0.00904)
Z		0.00358	9.47e-05	-0.00574	-0.026***	-0.072***	0.000722	-0.00141	-0.00102	-0.00041***	0.000384***
		(0.00754)	(0.000390)	(0.0131)	(0.00347)	(0.0111)	(0.000475)	(0.00830)	(0.00376)	(0.000133)	(0.000126)
Threshold	1.566	3.958	12.270	2.470	3.444	1.959	16.498	1.737	4.180	49.506	32.222
Percentile	21	66	50	64	79	13	18	47	70	90	46
P-value	0.000***	0.000***	0.297	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.008***	0.000***
Observations	15,850	15,850	15,850	9,559	9,559	8,061	10,372	9,742	14,200	15,850	15,850
R-squared	0.461	0.458	0.455	0.448	0.453	0.471	0.461	0.479	0.468	0.455	0.462
F-stat	158.4***	154.6***	153.0***	98.60***	100.5***	93.59***	120.8***	119.9***	151.5***	153.3***	157.7***

Notes: Robust standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1; All models include unreported time, industry and country fixed effects

7. Summary

This report considers the extent of R&D spillovers through intermediate inputs for a sample of up to 40 developed and developing countries. Results suggest that such spillovers are present and are economically important: A 1% increase in the growth rate of the R&D content of intermediates is associated with an increase in the growth rate of labour productivity of between 0.08% and 0.2%. Concentrating on the foreign R&D stock only leads to similar results, highlighting the importance of foreign R&D as a source of domestic productivity growth. Such results hide heterogeneity in outcomes however. We find significant differences in results when splitting the sample according to the value of measures of absorptive capacity and absorption barriers. To summarise the threshold results, we find that countries and industries initially further behind the technological frontier enjoy stronger foreign R&D spillovers. In their study, Falvey et al. (2007) found that spillovers were strongest in countries with intermediate levels of relative backwardness. Their study included a broader range of countries than the current one. Given that the current study doesn't include countries at very low levels of development, the results we obtain are therefore not inconsistent with those of Falvey et al. (2007). The results also support Falvey et al. (2007) as well as Crespo-Cuaresma et al. (2008) in finding that foreign R&D spillovers are stronger in countries with greater absorptive capacity (as measured by average years of secondary schooling and R&D spending). In terms of absorption barriers, the results are mixed. With the exception of regulations on temporary workers we find that stronger labour market regulation and greater union density is associated with lower foreign R&D spillovers, results again in line with Crespo-Cuaresma et al. (2008). Such results are also consistent with the arguments of Parente and Prescott (1994, 1999 and 2003). The evidence for other absorption barriers related to product market, financial and investment regulation provide no evidence of low regulation encouraging foreign R&D spillovers. Indeed, in these cases the reverse is found to be the case. Finally, we find that stronger levels of IPR protection can limit the extent of foreign R&D spillovers, possibly by limiting the ability to copy and borrow technology from abroad.

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Appendix

APPENDIX A: DATA SOURCES FOR THRESHOLD VARIABLES

OECD EMPLOYMENT PROTECTION INDICATORS

Data on employment protection are from the OECD's Indicators on Employment Protection (1985-2008), which collects data at the country level. We use data on four variables:

EPR – an indicator for dismissal of employees on regular contracts - calculated as a weighted sum of the following indices: Notification procedures; Delay involved before notice can start; Length of notice period at 9 months of tenure; Length of notice period at 4 years of tenure; Length of notice period at 20 years of tenure; Severance pay at 9 months of tenure; Severance pay at 4 years of tenure; Severance pay at 20 years of tenure; Definition of justified or unfair dismissal; Length of trial period; Compensation following unfair dismissal; Possibility of reinstatement following unfair dismissal

EPT – an indicator of the strictness of regulation on temporary contracts - calculated as a weighted sum of the following indices: Valid cases for use of fixed-term contracts; Maximum number of successive fixed-term contracts; Maximum cumulated duration of successive fixed-term contracts; Types of work for which temporary work agency employment is legal; Restrictions on number of renewals of temporary work agency contracts; Maximum cumulated duration of successive temporary work agency contracts

EPC – an indicator for additional regulation of collective dismissal - calculated as the unweighted average of the following indices: Definition of collective dismissal; Additional notification requirements for collective dismissals; Additional delays involved before notice can start for collective dismissals; Other special costs to employers of collective dismissals

All of these variables take a value between zero and six, with six being the most restrictive.

OECD PRODUCT MARKET REGULATIONS

Data on product market regulation are from the OECD's Indicators of Product Market Regulation. More details on the construction of this variable are available from Wölfl et al. (2009). The indices we use is based upon sub-indices capturing information on: State Control; Barriers to Entrepreneurship; and Barriers to Trade and Investment. The three indices are given a weight of one-third each when constructing the overall index. These sub-indices are themselves based upon further sub-indices. The variable takes on a value between zero and six, with six being the most restrictive.

OECD TRADE UNION DENSITY

Data on trade union density are from the OECD's Database on Trade Unions. Trade union density corresponds to the ratio of wage and salary earners that are trade union members, divided by the total number of wage and salary earners (OECD Labour Force Statistics). Density is calculated using survey data, wherever possible, and administrative data adjusted for non-active and self-employed members otherwise. The data is available annually at the country level.

HERITAGE FOUNDATION ECONOMIC FREEDOM VARIABLES

The Heritage Foundation produces annually an index of economic freedom. We use information on some of the sub-indices for this variable in our analysis. Details on their construction are written below.

Financial Freedom Index – is a measure of banking efficiency as well as a measure of independence from government control and interference in the financial sector. State ownership of banks and other financial institutions such as insurers and capital markets reduces competition and generally lowers the level of available services.

In an ideal banking and financing environment where a minimum level of government interference exists, independent central bank supervision and regulation of financial institutions are limited to enforcing contractual obligations and preventing fraud. Credit is allocated on market terms, and the government does not own financial institutions. Financial institutions provide various types of financial services to individuals and companies. Banks are free to extend credit, accept deposits, and conduct operations in foreign currencies. Foreign financial institutions operate freely and are treated the same as domestic institutions.

The *Financial Freedom Index* scores an economy's financial freedom by looking into the following five broad areas:

› The extent of government regulation of financial services,
› The degree of state intervention in banks and other financial firms through direct and indirect ownership,
› The extent of financial and capital market development,
› Government influence on the allocation of credit, and
› Openness to foreign competition.

These five areas are considered to assess an economy's overall level of financial freedom that ensures easy and effective access to financing opportunities for people and businesses in the economy. An overall score on a scale of 0 to 100 is given to an economy's financial freedom through deductions from the ideal score of 100. A value of 100 indicates negligible government interference and zero repressive intervention. To be consistent with the other indicators we reverse this, such that higher numbers are associated with more regulation.

The *Financial Freedom Index* relies on the following sources for data on banking and finance, in order of priority: Economist Intelligence Unit, *Country Commerce* and *Country Finance*, 2009–2012; International Monetary Fund, *Staff Country Report*, 'Selected Issues', and *Staff Country Report*, 'Article IV

Consultation', 2009–2012; Organisation for Economic Co-operation and Development, *Economic Survey*; official government publications of each country; U.S. Department of Commerce, *Country Commercial Guide*, 2009–2012; Office of the U.S. Trade Representative, *2011 National Trade Estimate Report on Foreign Trade Barriers*; U.S. Department of State, *Investment Climate Statements*, 2009–2012; World Bank, *World Development Indicators* 2012; and various news and magazine articles on banking and finance.

Investment Freedom Index – in an economically free country, there would be no constraints on the flow of investment capital. Individuals and firms would be allowed to move their resources into and out of specific activities, both internally and across the country's borders, without restriction. Such an ideal country would receive a score of 100 on the investment freedom component of the *Index of Economic Freedom*. To be consistent with the other indicators we reverse this, such that higher numbers are associated with more regulation.

In practice, most countries have a variety of restrictions on investment. Some have different rules for foreign and domestic investment; some restrict access to foreign exchange; some impose restrictions on payments, transfers, and capital transactions; in some, certain industries are closed to foreign investment. Labour regulations, corruption, red tape, weak infrastructure, and political and security conditions can also affect the freedom that investors have in a market.

The *Investment Freedom Index* evaluates a variety of restrictions that are typically imposed on investment. Points are deducted from the ideal score of 100 for each of the restrictions found in a country's investment regime. These investment restrictions (and the extent of the restrictions) are: National treatment of foreign investment (no national treatment; some national treatment, some pre-screening; some national treatment or pre-screening); Foreign investment code (no transparency and burdensome bureaucracy; inefficient policy implementation and bureaucracy; some investment laws and practices non-transparent or inefficiently implemented); Restrictions on land ownership (all real estate purchases restricted; no foreign purchases of real estate; some restrictions on purchases of real estate); Sectoral investment restrictions (multiple sectors restricted; few sectors restricted; one or two sectors restricted); Expropriation of investments without fair compensation (common with no legal recourse; common with some legal recourse; uncommon but occurs); Foreign exchange controls: (no access by foreigners or residents; access available but heavily restricted; access available with few restrictions); and Capital controls (no repatriation of profits, all transactions require government approval; inward and outward capital movements require approval and face some restrictions; most transfers agreed with some restrictions). Additional points may be deducted for security problems, a lack of basic investment infrastructure, or other government policies that indirectly burden the investment process and limit investment freedom.

The *Investment Freedom Index* relies on the following sources for data on capital flows and foreign investment, in order of priority: official government publications of each country; Economist Intelligence Unit, *Country Commerce*, 2009–2012; Office of the U.S. Trade Representative, *2012 National Trade Estimate Report on Foreign Trade Barriers*; and U.S. Department of Commerce, *Country Commercial Guide*, 2009–2012.

APPENDIX B: THRESHOLD REGRESSION

Threshold models have in recent times received a great deal of attention as a means of modelling parameter heterogeneity and non-linearities. In a series of papers Hansen (1996, 1999 and 2000) develops a technique that allows the sample data to jointly determine both the regression coefficients and the threshold value for OLS and (non-dynamic) fixed effects panel models. The threshold model for a single threshold can be written as:

$$y_i = \alpha_0 + \delta_1 x_i 1(q_i \leq \lambda_1) + \delta_2 x_i 1(q_i > \lambda_1) + \varepsilon_i$$

where 1 is the indicator function and q_i is the threshold variable. Here the observations are divided into two regimes depending on whether the threshold variable is smaller or larger than λ_1. The two regimes are distinguished by different regression slopes, δ_1 and δ_2. Chan (1993) and Hansen (1999) recommend estimation of λ_1 by least squares. This involves finding the value of λ_1 that minimises the concentrated sum of squared errors. In practice this involves searching over distinct values of q_i for the value of λ_1 at which the sum of squared errors is smallest, which is then our estimate of the threshold. Once we have an estimate for the threshold it is straightforward to estimate the model. Hansen (2000) extends this method to the case of non-dynamic fixed-effects panel models.

Having found a threshold it is important to determine whether it is statistically significant or not, that is, to test the null hypothesis; $H_0: \delta_1 = \delta_2$. Given that the threshold λ_1 is not identified under the null, this test has a non-standard distribution and critical values cannot be read off standard distribution tables. Hansen (1996) suggests bootstrapping to simulate the asymptotic distribution of the likelihood ratio test allowing one to obtain a p-value for this test. Firstly, one estimates the model under the null (i.e. linearity) and alternative (i.e. threshold occurring at λ_1). This allows one to construct the actual value of the likelihood ratio test (F_1):

$$F_1 = \frac{S_0 - S_1(\lambda_1)}{\sigma^2} \qquad \text{where } \sigma^2 = \frac{1}{n(t-1)} S_1(\lambda_1)$$

Here S_0 and S_1 are the residual sum of squares from the linear and threshold models respectively. Using a parametric bootstrap (see Cameron and Trivedi, 2005) the model is then estimated under the null and alternative and the likelihood ratio F_1 is calculated. This process is repeated a large number of times. The bootstrap estimate of the p-value for F_1 under the null is given by the percentage of draws for which the simulated statistic F_1 exceeds the actual one.

The approach is also easily extended to consider more than one threshold. While it is straightforward to search for multiple thresholds, it can be computationally time-consuming. Bai (1997) has shown, however, that sequential estimation is consistent, thus avoiding this computation problem. In the case of a two threshold model this involves fixing the first threshold and searching for a second threshold. The estimate of the second threshold is then asymptotically efficient, but not the first threshold because it was estimated from a sum of squared errors function that was contaminated by the presence of a neglected regime. Bai (1997) suggests estimating a refined estimator for the first threshold, which involved re-estimating the first threshold, assuming that the second threshold is fixed. The test of significance of the second threshold proceeds along the same lines as described above, with the null and alternative hypotheses being of a one and two threshold model respectively.

APPENDIX C: SECTOR CLASSIFICATIONS

Table C1 / Sector classifications

WIOD Code	WIOD Sector Name
AtB	Agriculture, Hunting, Forestry and Fishing
C	Mining and Quarrying
15t16	Food, Beverages and Tobacco
17t19	Textiles and Textile Products and Leather, Leather and Footwear
20t22	Wood and Products of Wood and Cork and Pulp, Paper, Paper , Printing and Publishing
23t25	Coke, Refined Petroleum and Nuclear Fuel , Chemicals and Chemical Products and Rubber and Plastics
26	Other Non-Metallic Mineral
27t28	Basic Metals and Fabricated Metal
29	Machinery, Nec
30t33	Electrical and Optical Equipment
34t35	Transport Equipment
36t37	Manufacturing, Nec; Recycling
E	Electricity, Gas and Water Supply
F	Construction
50	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel
51	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles
52	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods
H	Hotels and Restaurants
60	Inland Transport
61	Water Transport
62	Air Transport
63	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies
64	Post and Telecommunications
J	Financial Intermediation
70	Real Estate Activities
71t74	Renting of Machinery and Equipment and Other Business Activities
L	Public Admin and Defence; Compulsory Social Security
M	Education
N	Health and Social Work
O	Other Community, Social and Personal Services
P	Private Households with Employed Persons

APPENDIX D: STATIONARITY TESTS

Coe and Helpman (1995) in their study found that their data exhibited a clear trend, but that a cointegrating relationship existed between the variables, which allowed them to estimate their model in levels using OLS. They chose not to report t-statistics for their results, because at the time the asymptotic distribution of the t-statistic was unknown. As Kao et al. (2000) pointed out however, the OLS estimator is (super-) consistent even under panel cointegration, but has a second-order asymptotic bias that leads to invalid standard errors. Kao et al. (2000) recommend alternative estimation procedures, such as Fully Modified OLS (FMOLS) and Dynamic OLS (DOLS), which are able to provide valid t-statistics in the presence of non-stationary data.

We use the Im-Pesaran-Shin test (IPS) (2003) to test whether our variables of interest are stationary or not. In contrast to the Levin-Lin-Chu (LLC) and the Harris-Tzavalis and Breitung tests, the IPS test relaxes the assumption of a common ρ for the whole panel. The method also allows for different serial correlation properties across cross-section units. The method involves averaging individual unit root tests based on the Augmented Dickey-Fuller (ADF) test. The null hypothesis is that each series in the panel contains a unit root ($\mathrm{H}_0\colon \rho_i = 0\ \forall i$), with the alternative being that at least one of the series is stationary.

Table A2 reports the results from the IPS test for the main variables of interest in both levels and first differences. The number of lags in the ADF test for each cross-section is determined by the Schwarz-Bayesian criteria where we impose a maximum number of four legs. In addition to the test statistic, Table A2 also reports the average number of lags chosen by this criterion. The results in the top-half of Table A2 are mixed. While we can reject the null hypothesis that all of the series contain a unit root in favour of the alternative that at least one does not at the 1% significance level for the main R&D variables, we cannot reject the null hypothesis of a unit root for the measure of labour productivity and the capital-labour ratio. When considering the variables in first differences we find that we can reject the null hypothesis of a unit root for all variables. For this reason we estimate our model in first differences.[17]

Table A2 / Im-Pesaran-Shin unit root test results

	Test Statistic	p-value	Average Number of Lags
Levels			
$\ln y$	11.82	1.0000	1.35
$\ln k$	3.88	0.9999	1.95
$\ln F$	-2.55	0.0054***	1.18
$\ln F_D$	-3.91	0.0000***	1.10
$\ln F^d$	-6.35	0.0000***	1.22
$\ln F_D^d$	-6.52	0.0000***	1.20
First Differences			
$\Delta\ln y$	-45.75	0.0000***	1.22
$\Delta\ln k$	-75.78	0.0000***	1.98
$\Delta\ln F$	-53.09	0.0000***	1.25
$\Delta\ln F_D$	-55.36	0.0000***	1.22
$\Delta\ln F^d$	-56.14***	0.0000***	1.25
$\Delta\ln F_D^d$	-57.01	0.0000***	1.22

Notes: The number of lags is series specific and is based upon the Schwarz-Bayesian information criteria (maximum number of lags considered is 4).

17 Results from the Westerlund cointegration test suggest a lack of cointegration in the levels regression, which thus supports the use of the first difference specification.

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