Assessing the relative importance of multiple channels for embodied and disembodied technological spillovers

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Abstract

With ever increasing global integration, productivity improvements depend not only on in-house innovative efforts, but on those of international partners as well. This paper explores the impact of foreign R&D on productivity and technical efficiency of countries by considering three major channels of embodied and disembodied spillovers, namely trade, foreign direct investment and patenting, and controlling for direct licensing of foreign technologies. Furthermore, it contrasts these effects across 47 developed and transition countries between 1990 and 2009. Overall, I find that trade remains the dominant factor behind productivity and technical progress, while the effects of FDI- and patent-related spillovers are significantly smaller. The effect of foreign patenting is larger in developed nations while imports, inward FDI and foreign technology licensing are important sources of know-how for transition economies. The aggregate gains from spillovers appear larger for latter, confirming their significance in the process of development and catching-up.

Keywords: R&D spillovers; trade; FDI; patents; licensing;

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1 Introduction

Over the past decades, globalization has accelerated both the rate of technological innovation and its diffusion worldwide [7]. The literature postulates research and development (R&D) efforts as the cornerstone of productivity and economic growth [38,70]. However, few can reap these benefits, since most R&D is carried out exclusively in a handful of industrialized nations, with few new players joining this club [42][1]. As a result, most countries depend on knowledge inflows from abroad to augment their productivity, and ultimately, economic competitiveness [49]. Thus, identifying the impact of these technology spillovers and the channels through which they operate, will help understanding the existing worldwide discrepancies in income per capita [41], and enunciate pertinent policy insights for developing and transition economies competing in global markets [34].

Technology transfer occurs between countries, sectors, firms or individuals and can take many forms. The literature investigates technological content that spills over via imported intermediates [27,54], equipment of multinationals [2,39,71] or skilled human capital [66,53]. Moreover, technical knowledge may diffuse in disembodied forms such as patents [8,76], licensing agreements [63,83], R&D contracting and outsourcing [20,69], and communication [74,82]. While patenting has been analyzed quite extensively [31,54], downstream revenues from it and other forms of intellectual property remain relatively unexplored, especially in large cross-sections [60]. Secondly, while theoretical arguments support multiple channels through which technical know-how migrates between firms, sectors and countries, empirical validations of these avenues remains rather scant [39,54]. Moreover, a significant problem is the lack of reliable data for many developing and transition economies, exactly those for which theory predicts larger spillovers [64] with crucial implications for exports [5], growth and catch-up [32].

This paper proposes several contributions to the literature as follows. First, it quantifies

[1] Hall [42] shows that the concentration of R&D activities is decreasing slowly over time from 0.78 in 1999 to 0.75 in 2005, as opposed to an unchanged 0.69 in both years for GDP.

both *embodied* and *disembodied* sources for spillovers of foreign R&D. To this purpose, it considers four alternative channels for foreign technological content, namely trade and FDI for embodied knowledge, plus international patenting and licensing for disembodied one. With the exception of trade, the magnitude and effects of other channels of diffusion are still debated in the literature [10,35]. Moreover, while the effects of these channels have been explored in isolation by previous work, assessing their relative effectiveness in diffusion of technology remains an open question [49]. Secondly, this work contrasts the effects of spillovers across a panel of both *developed* Western economies and *transition* countries from Eastern Europe (CEECs) and the Commonwealth of Independent States (CISs). The latter had mixed performance both in terms of R&D and growth rates, as a result of past dependence in terms of scientific and economic specialization to the socialist era [16,52]. Finally, this study deals with issues related to non-stationarity, cointegration and dynamic estimation to obtain robust results on the effect of embodied and disembodied spillovers on productivity and technical efficiency of countries.

The empirical results confirm the paramount role of trade in diffusion of new technologies, consistent with previous findings [25,54,81]. FDI is particularly important for transition economies, as multinationals (MNEs) boost significantly host countries productivity and GDP levels [34]. The spillover effects from foreign patents are prevalent in developed economies that utilize this channel efficiently to tap new knowledge produced by MNEs active in these markets [80]. Oppositely, emerging markets lack the capacity and the intellectual property enforcement tools to attract MNEs to patent domestically or set-up R&D facilities. Finally, direct acquisition of foreign technologies through licensing agreements translates into greater total factor productivity and technical efficiency gains for transition economies that are further from the global technological frontier. In today's global economy densely inter-linked through trade, investment and knowledge exchanges, developing countries benefit significantly from foreign spillovers to accelerate their development and "catch"-up with the industrialized world. These results shed light on the relative importance and effectiveness of these channels and provide concrete pointers for policy-makers in these countries. Trade, FDI and bilateral patenting with developed and R&D intensive countries all bear positive effects on productivity levels [19,50]. However, effects vary across countries based on their portfolio of trade,FDI and innovating partners and their relative R&D intensity[2]. These indirect sways are stimulated by good institutions [18,26,75], highly skilled human capital [9,62] and incentives for foreign firms to develop local high-tech capabilities, such as local R&D units [29,43]. Unlike embodied spillovers, imports of technologies contribute directly to total productivity via domestic firms that make these purchases. This represents a more expensive, yet faster, alternative for developing countries to move closer to the world's technological frontier, and recent history provides us with several examples of countries (e.g. Japan, Taiwan, South Korea and China) that have been successful utilizing this strategy to boost their economic performance[3].

The rest of the paper is organized as follows. Next section provides a discussion of the literature on the international R&D spillovers. Section 3 details the empirical framework used, starting with the background model, data and variables employed, econometric investigation and subsequent checks for robustness. Finally, Section 4 concludes and discusses policy implications stemming from this work.

2 Theoretical background

2.1 Embodied versus disembodied spillovers

R&D investments spur new knowledge about materials and processes, ways of recombining them to produce new goods and services. However, in practice, such benefits are impossible to be fully internalized. Thus, it is interesting to quantify the effects of these *"spillovers"*

[2]By having extensive networks in all these areas, a country has more chances of drawing upon multiple sources of spillovers: imports, inward FDI and inward patents

[3]During 2001 to 2006, China has imported technology worth more than 90 billion US$, mostly from EU, Japan and the US.

throughout a sector or economy, and secondly seek ways to maximize them. Endogenous growth models see R&D spillovers as a significant source of growth, and starting with the work of Coe and Helpman [27] a large body of literature has brought numerous empirical evidence to support to this conventional wisdom [71].

However, the type of underlying R&D process plays an important role in identifying and classifying spillovers. Los and Verspagen [58] classify R&D efforts as "process-oriented" (aiming at lowering production costs) and "product-oriented" (focusing on developing new products or improving quality of the existing ones). This classification has a particular influence on the type of spillovers analyzed, since process R&D is usually protected using *secrecy*, while product R&D is exposed in produced goods. Furthermore, in a famous contribution, Griliches [37] distinguishes two types of R&D externalities, namely the *knowledge spillovers (disembodied)* and *rent spillovers (embodied)*. The latter implies that the price of imported intermediate goods does not fully reflect the amount of innovative efforts undertaken to develop them, mainly due to competitive pressures in oligopolistic markets [24]. In contrast, *spillovers from knowledge* arise because due to imperfect appropriability without involving any economic transaction[4]. While disembodied spillovers are difficult to quantify due to their immaterial nature, common empirical strategies involve adopting various proxies, such as technological proximity measures [13,54,65]. Moreover, both types are highly correlated across countries and time posing additional econometric problems.

2.2 Multiple channels for technological spillovers and learning

2.2.1 Imports

Starting with Coe and Helpman [27] and Coe et al. [28], the literature has documented in great detail the role of *trade* (particularly, imports) in facilitating the exchange of tech-

[4]By definition, knowledge is a quasi public good with non-rival and non-excludability characteristics. For example, it would be extremely hard to prevent one from using knowledge (e.g. using the Pythagorean theorem to find the length of a triangle's side) and moreover this usage will not diminish the quantity or quality of this knowledge left for others to use.

nological information between firms, industries and countries [25,53,54]. Studies employing sectoral data for OECD countries confirm that the foreign R&D spillovers greatly influence domestic productivity, complemented by intra- and inter-sectoral effects [1]. These results are also in line with the product life cycle theory of Vernon [78], where development of new cutting-edge technologies and products takes place in developed nations, and then diffuses slowly to their Southern neighbors. Moreover, when analyzing worldwide exports at a fine 6 digit granulation, Hausmann et al. [44] finds that most developed nations are specialized in sophisticated and high value-added products which confers them significant competitive advantage. Furthermore, all these economies are clustered in a "core" of the global trade network (i.e. G-20 or OECD countries), which is very intensive both in terms of linkages and in terms of R&D flows [74]. In contrast, transition countries (CEECs and CISCs) tend to have much lower domestic R&D intensity (both public and private one) and are divided around major regional trade poles, namely EU and Russia [16][5].

2.2.2 Foreign direct investment

FDI is emphasized in the international business literature as an important carrier of spillovers, usually through expansions of multinational firms (MNEs) that transplant new equipment and know-how to local markets [47,80,83]. Prior to the crisis, the volume and impact of FDI has increased significantly worldwide from year to year.[6]. While the first FDI inflows to transition countries were quite small and geographically confined to Central Europe (Poland, Czech Republic or Hungary), the post-2000 wave focused on far-Eastern firms in Russia, Ukraine and Kazakhstan. Overall, the bulk of investment concentrates in the tertiary sector (trade, finance, communication), manufacturing and resources (especially for Russia and other CIS states). The most important partners are European (Germany, Austria and

[5] South Eastern European countries have increased their shares of exports to the EU from 54% in 1993 to 62% in 2003; during the same period, the CIS countries decreased it from 46 to 39%, while the intra-regional exchanges doubled from 38 to 78%.

[6] Globally, FDI inflows soared in 2006 to $ 1.306 billion, up 38 percent from 2005 and close to the record level of $1,411 billion reached in 2000. Inflows increased in all three groups of economies (developing, developed and transition) according to UNCTAD (2007).

Netherlands) followed by the USA and Japan. The spillovers from multinationals (MNEs) on productivity of domestic firms arise through several mechanisms [72]: i) demonstration effects (adoption or imitation of MNE technology by domestic firms); (ii) labor turnover (workers possessing new knowledge, tacit in essence, switch from MNE to domestic employers or start new businesses); iii) vertical linkages (MNEs transfer technology to their suppliers or customers). Despite the strength of these arguments, the empirical evidence is quite mixed. While early studies [2,30,82] find no effects or even negative spillovers from foreign firms on domestic productivity, more recent findings [34,36,53,83] argue the opposite[7]. Given the inconsistency of these findings, further explanations have included also the role of absorptive capacity (either in the form of existing knowledge base or human capital) and institutional settings [12,18]. The level of analysis (firm-, sector- or country-) has also implications in terms of results. Although firm level studies benefit from reliable data, they often suffer from selection bias or country specific heterogeneity; similarly, sector and country level studies usually control for these aspects, but lack in terms of precision and ability to isolate effects across firms [17].

2.2.3 Foreign patenting

Another channel through which technological content crosses borders is *patenting* done by foreign firms and individuals in host markets. As new research gets patented, it becomes available to the public and may be used to build upon and develop new technologies and products. Bilateral patent statistics provide a direct link between origin and destinations of knowledge, and prior research suggests that this tends to be geographically confined [46] with national boundaries still relevant as barriers for technology diffusion [73][8]. Multinational firms (MNEs) entering other markets often protect some of their technological portfolio in

[7]In some cases of FDI in transition countries there is clear evidence of technology transfer (e.g. Volvo in Poland, Valeo in Czech Republic or Nokia in Romania) but MNEs can also opt for medium- or low-tech affiliates, depending on characteristics of the industry, markets, legislative norms, etc.

[8]For example, Romania had 1,003 patent applications in 2006 of which 78% were from domestic inventors, 8% US (109), 3% German (44), 2% French (44) and 1% Japanese (22). Overall, there is significant heterogeneity across countries in terms of these ratios and the origin of foreign applications.

these countries by having domestic patents issued. Thus, these patents surpass national and language barriers, with immediate effects on knowledge levels in these markets, eluding the effect of geographical, technological and cultural distances between home and host countries. Regarding the 47 countries considered in this study, the ratio of foreign patent applicants of the total is higher (on average 41% between 1995 and 2009) in transition countries, all behind the technology frontier and still rebuilding and restructuring their innovative competencies [50].

Patents provide a straightforward channel for knowledge spillovers linking directly users and sources of technologies [31]. Closely related to commercial prospects of new inventions, patents are widely accepted proxies for innovation in the innovation literature, used to explore various issues such as productivity [81] or foreign direct investment [14]. However, the literature reports some important caveats of using patents as an indicator for innovation [8,77]. First, not all knowledge *is* patentable, and moreover, it does not *get* patented, so that patents are just a piece in a bigger realm of innovation in a country. Secondly, most patents worldwide are granted at the "Triadic" (USA-Japan-EU) patent offices, hence in international comparisons developing and transition countries will likely suffer from a downward bias (lower patenting) due to economic and cultural specifics that affect their international patenting rates. This analysis will control for these issues and use patenting in foreign markets as weight for spillovers from abroad. However, I expect that, due to the flows of patenting and citations mainly occurring within Triad, and their relatively narrow geographical reach even in these countries as pointed in the literature, patent related spillovers to be less important (smaller in magnitude) than the main channels at work (trade and investments). Moreover, the relative difference in market size implies that the most important technologies will be patented in major markets (i.e. developed nations), hence generating greater spillovers there than otherwise.

2.2.4 Licensing of technologies

Lastly, a different branch of literature argues that the correlation between foreign R&D stocks and productivity improvements reflects merely diffusion effects, and more importantly, it fails to explain the underlying mechanisms of this process [6]. This work documents the existence of sizeable markets for technology in various industries (chemical, software and electronics) providing clear measures of technological transfers between countries. In contrast to previous channels, *acquisition of technology* is a faster and more efficient way to import technology across borders with strong effects on productivity [9]. Cassiman and Veugelers [21] distinguish between embodied technology via assets such as new personnel or (parts of) other firms and disembodied technology through licensing, R&D contracting, outsourcing or technological consulting. Moreover, Cassiman and Veugelers [20] find that firms tend to use these external technology sources to complement existing in-house competencies. Hence, aggregating these external payments and royalties the country level will provide direct evidence of technology transfers in an international context [60] and with immediate impacts on productivity of domestic firms. Within our dataset, all transition countries together spend on average, less than the UK, the European leader in this respect. [10] However, data on international royalties and licensing payments has its own limitations in terms of measuring technology exchanges. First, in some cases most of these payments occur between MNEs and their affiliates without involving directly domestic firms. Secondly, there is an intricate relationship between FDI and licensing, one that is hard to disentangle in practice. Several case studies document in detail gains from licensing in developing countries [22,29] but overall, the literature remains deficitary in generalizing these results at the firm [23,58] and country level [60]. Building on this literature, this study considers patenting and licensing as complementary channels

[9] In the 1950s and 1960s, Japan kept itself mostly closed to FDI and conditioned MNE presence to transfers of technology to Japanese firms. Today, China mandates incoming MNEs to form joint ventures with local partners as opposed to green-field projects. The aim is to facilitate knowledge transfers and assimilation for domestic firms

[10] In 2005, CEECs spent over US$ 5 bln. to acquire technology from abroad while the total payments for the UK was around US$ 9 bln. Among them, only Russia, Hungary and Poland were above the 1 bln. threshold.

for disembodied technology diffusion. While patent flows from a foreign country expand the *available knowledge stock* of the host nation's firms to build, adopt, imitate or patent around it, these process is subject to a stochastic rate of success that depends greatly on its absorptive capacity [51]. In contrast, technological payments provide a direct measure of *technological imports ready to be implemented* in the production process with immediate effects [20].

Testing together the concurrent effects of all these channels is a daunting task both in conceptual and empirical terms [37]. It involves measuring several embodied and disembodies sources of spillovers and disentangling their effects through efficient estimation techniques. This study provides a first attempt at this challenging task by looking at imports, inward FDI, incoming foreign patents and direct imports of technologies in a panel of 47 economies over the period 1990 to 2009.

3 Empirical framework

3.1 Estimation model

Given the proposed research objective (i.e. to disentangle the concurrent effects of several channels for R&D spillovers) the analysis is carried out at the country level employing the following Cobb-Douglas production function:

$$Y = Ae^{\lambda}L^{\alpha}K^{1-\alpha}DRD^{\psi}S_D^{\eta}S_E^{\phi} \tag{1}$$

where Y is the aggregated output (total GDP), A a constant, λ the rate of external technological change, L and K are the labor and respectively, capital employed in production. DRD^{ψ}represents the domestic stock of knowledge while S_D^{η} and $S_E^{\phi}$are the total foreign inflows of disembodied and respectively, the embodied technology. Time and country indexes have been omitted to preserve simplicity. Taking logarithms and defining total factor productivity (TFP) as a measure of the effects in total output caused by technological improvements and efficiency gains, the equation can be rewritten as:

$$\ln TFP = \lambda + \psi \ln DRD + \eta \ln S_D + \phi \ln S_E \tag{2}$$

Consistent with our previous conjectures these external flows are determined by:

$$S_E = S^{TRADE} + S^{FDI} \tag{3}$$

$$S_D = S^{PAT} + M^{TECH} \tag{4}$$

where the *embodied technology* transfer from a country j to i occurs via two channels: imports of intermediate goods (S^{TRADE}) and foreign direct investment (S^{FDI})[11]. The sources of *disembodied technology* include spillovers from foreign patenting (S_{PAT}) done in country i by entities of j as well as direct technology purchases (M^{TECH}) from country j. As a result of international trade and investment, both domestic and foreign intermediate goods can be employed in i's production. The range of foreign knowledge is captured in this model by a flow weighted foreign R&D matrix, where the flows are bilateral imports and inward FDI. Similarly, patented knowledge in country j (recipient) resulted from i's R&D investments contributes to development of new intermediate goods in j, either through local R&D efforts or direct licensing of technology. The following equations formalize these arguments by computing these spillovers as weighted foreign R&D stocks, following Lichtenberg and Van Potteslberghe de la Poterie [54]:

$$S_{it}^{TRADE} = \sum_{j=1}^{n} M_{ijt} * \frac{FRD_{jt}}{Y_{jt}} \tag{5}$$

[11] FDI can act as a channel for both embodied (machinery, equipment) and disembodied (human capital, know-how) technology transfer. For simplicity, I consider FDI as a source of embodied R&D spillovers.

$$S_{it}^{FDI} = \sum_{j=1}^{n} FDI_{ijt} * \frac{FRD_{jt}}{Y_{jt}} \tag{6}$$

$$S_{it}^{PAT} = \sum_{j=1}^{n} PAT_{ijt} * \frac{FRD_{jt}}{Y_{jt}} \tag{7}$$

where i represents the home or recipient country and j is the foreign one. M_{ijt} is the flow of goods from i to j, FDI_{ijt} is the flow of investment from i to j, and PAT_{ijt} is the number of patents with assignees from j that are patented in i, FRD_{jt} is the stock of R&D of country j (foreign) and Y_{jt} is the GDP of country j, all in year t. Spillovers are computed as the sum of all weighted R&D intensity of all trade, investment and patenting partners (i.e. the js) of a country i. The greater R&D intensity of these partners or the absolute value of these exchanges (imports, FDI inflows, foreign patenting)increase, the greater *i's* potential spillovers will be. Accounting for all these spillovers the full specification to be tested becomes:

$$\ln TFP_{it} = \lambda_i + \psi \ln DRD_{it} + \eta_1 \ln S_{it}^{TRADE} + \eta_2 \ln S_{it}^{FDI} + \phi_1 \ln S_{it}^{PAT} + \phi_2 \ln M_{it}^{TECH} + \varepsilon_{it} \tag{8}$$

where λ_i is a country specific intercept and ε_{it} is a mean zero term. I am particularly interested if trade spillovers are greater for developed nations than otherwise ($\eta_1^{develop} > \eta_1^{transit}$), the impact of FDI on productivity is smaller than that of trade ($\eta_2 < \eta_1$), while the impact of patent spillovers is smaller than that of FDI ($\phi_1 < \eta_2$) and that of direct purchases of foreign technologies ($\phi_1 < \phi_2$).

3.2 Data and variables

As the source of technological spillovers I consider all 25 OECD countries that are responsible for most of world's R&D investments (81% in 2004) and high-tech production. The time span considered is 1990 to 2009, since prior to 1990 transition countries from Eastern Europe and Central Asia were virtually closed to international trade and investments. This section details the construction of variables of interest. Additional details or the variable construction and data sources used are presented in `Appendix A`.

Total Factor Productivity (TFP) is determined as the residual from the aggregated output production function (1) using the country's stock of capital, labor force and output assuming constant returns to scale and shares of 0.65 and 0.35 to labor and capital, frequently employed in the literature [25,27,81]. Moreover, robustness checks were performed to insure the reliability of these estimates[12]. Comparable data on GDP and employment comes from the Groningen Growth and Development Center and the Conference Board, Total Economy Database. The values of capital stock are computed using data on aggregate investment share as a percentage of GDP from the World Penn Tables version 6.2.

As an alternative measure, I compute a *technical efficiency* index using stochastic frontier analysis on the same aggregated variables (output, labor, capital) following the methodology of Battese and Coelli [11]. This method allows one to distinguish between various components of productivity growth, such as a shift in production function for a country (*technical progress*) or a movement along it (*technical efficiency*). Frontier techniques are particularly interesting since the separation of efficiency effects and technical change has a direct interpretation in terms of the catch-up debate. In this study, I am interested in the latter and its relationship with international R&D spillovers.

Estimates of domestic and foreign *R&D capital stocks* are based on the gross expenditure on R&D (GERD) that includes both the business sector spending and the public R&D from universities or research institutes. In the case of origin countries of origin for spillovers (OECD 25) data comes from OECD's Main Science and Technology Indicators 2007, while for transition countries I construct R&D stocks using data on GERD as a percentage of GDP (from UNESCO Statistical Yearbooks, national statistics and the World Development Indicators 2011 from the World Bank). To compute R&D stocks I employ the perpetual inventory method described in `Appendix A`.

[12] a parametric estimation with second and third lags of the explanatory variable as instruments revealed coefficients close to our assumption, namely 0.33 for capital and 0.63 for labor.

The *trade related R&D spillovers* are computed following equation (5). Bilateral trade flows are obtained from IMF's Direction of Trade 2011 (DOTS). *FDI spillovers* are computed in a similar manner following equation (6). Detailed inward FDI flows are procured from the individual statistics of most of the OECD countries as reported in the annexes of UNCTAD's World Investment Report (various editions). The advantage of the former, as opposed to the commonly employed OECD International Direct Investment Statistics, is its superior consistency over time. However the UNCTAD data is checked for consistency, and gaps are addressed using OECD investment data where available.

To quantify *disembodied R&D spillovers*, I use the WIPO (World International Patent Office) data on patents granted to foreign and domestic applicants worldwide. This dataset benefits from a long time dimension going back to the 1800s in some cases, detailed bilateral flows and extensive country coverage, covering also transition countries from Eastern Europe and Central Asia. However, its main drawback is that it provides only patent counts (grants and applications) without additional information (e.g. patent citations) that could improve accuracy of quantifying such spillovers. To cope with the inherent differences in patent granting and success rated across countries, I opt for an indicator based on *patent applications* rather than grants.

To analyze *disembodied technology trade*, I employ use flows of royalties and license fees as a measure of technology purchases from abroad (World Development Indicators 2011). These are payments and receipts between residents and non-residents of a country for the authorized use of intellectual property (such as patents, copyrights, trademarks, industrial processes, and franchises) usually through licensing agreements.

Human capital is an important factor that affects TFP [65,66,67] both directly as qualitative parameter of the labor force engaged in production activities (L), and indirectly by enhancing a country's absorptive capacity. Therefore following previous studies [26,63], I include the level of human capital as a control in all regressions. This variable (log school) is the log of the average number of school years completed by the adult population aged 25 and over. The data are taken from [7], and values are reported every five years. In order to take advantage of the temporal dimension of the dataset, I have interpolated these values linearly for the rest of intermediate years.

3.3 Preliminary analysis

To assess the relative effectiveness of the proposed four channels, I follow the specification described in equation (8). However, considering the close co-movements of these variables over time, multicollinearity may become an issue for our estimations. Thus, in order to minimize the incidence of such econometric problems I will limit the number of controls used in the regressions to just the crucial ones (domestic R&D stocks, human capital endowments) presented in the literature. Instead of using a large battery of control variables, to account for unobserved heterogeneity among countries, I include country fixed effects in all estimations. Table 1 presents descriptive statistics, while Table 3 reports the correlation matrix for the variables of interest. Table 2 distinguishes between transition (*trc*) and developed Western economies (*wec*) in the dataset, showing that there are significant differences between these two groups both in terms of productivity (technical efficiency) as well as in magnitudes of spillovers.

Secondly, to avoid spurious regression, since it is well known that some of these variables tend to be non-stationary, I perform unit root and cointegration tests for all estimated regressions. Last four columns of Table 1 show the results of several panel unit root tests suggested by Levin et al. [56], Im et al. [45], Breitung [15] and Hadri [40]. The results of these tests suggest that these variables are not stationary. Thus, to be able to use regression analysis for estimating equation (5) one needs to find out a cointegration relationship among these variables. I employ the three most powerful tests in this context proposed by Pedroni [68][13]. Their values and their significance levels are reported under each of the models

[13] These seven residual-based tests have a null hypothesis of no cointegration and allow for heterogeneous cross sectional variance. Pedroni [65] concludes that the parametric *group-t statistic* and *panel-t statistic* appear to have the highest power, followed by the *panel-rho statistic*.

estimated. Overall, in most cases the null of no cointegration is rejected, which makes the fixed effects estimations legitimate (not spurious).

Finally the estimation of spillovers effects on productivity is usually confronted with problems of spurious regression and reverse causality[14]. To increase the robustness of these conclusions, all estimations are carried out employing a dynamic ordinary least squares estimator (DOLS) with country and time fixed effects. This estimator is shown in the literature to outperform in terms of efficiency other alternatives in the case of small cointegrated panels [46] and is derived from the simple OLS one by adding extra lags and leads of the first-differentiated regressors. The latter are meant to control for endogeneity and estimate the standard errors on the basis of a long-run serial correlation robust error covariance matrix.

3.4 Econometric results

Table 4 reports the main estimations for the effects of foreign R&D spillovers on total factor productivity. The first two variables (S^{FDI}, S^{TRADE}) capture the impact of rent spillovers or embodied knowledge via two channels (trade and FDI), while the other two (S^{PAT}, M^{TECH}) focus on disembodied sources of knowledge employing technology imports and foreign patenting as carriers. The models distinguish between general effects when considering all countries (*all*) in the sample, transition economies (*trc*) and respectively developed economies of Western Europe (*wec*). The reason behind this segregation is to explore relative impacts of these channels for different sets of countries; the underlying assumption, based on prior findings, is that the nature of trade, patenting and FDI differs significantly between a developed and a transition or developing economy [23].

Models 1-3 examine the effect of embodied (imports and FDI) foreign spillovers on productivity. Right from the start, trade's coefficient is significantly bigger than FDI's, and remains the same throughout the remaining estimations (Model 2-9). Regardless of specifi-

[14] As Griliches [35] points out, the problem is to establish a causal relationship since future output and productivity depend on past R&D, while in turn, the latter is a function of past output and expectations about its future performance.

cations, there is strong support for our first hypothesis, that spillovers from FDI are lower than those from trade, both in the case of Western (Model 2) and Eastern Europe/Central Asia (Model 3). Domestic R&D stocks appear to impact productivity only in the case of advanced economies that invest heavily in R&D both from private and public sources.

In a similar fashion, Models 4 through 6 focus on disembodied sources of technology (foreign patents at the domestic patent office, plus royalties and payments for foreign technologies), and their relative impact on developed versus developing countries. The results suggest greater effects of patent spillovers on productivity that those from direct licensing in the case of Western Europe, while for transition countries the opposite holds. Patent related spillovers are prevalent in Western (developed) countries, where more patents are exchanged between holders and firms from other developed nations. This is consistent with previous conclusions on the curvilinear effects of patenting on growth, suggesting that patent related spillovers are more likely to occur at the extremes of the global income distribution [62], whereas all transition countries fall in the middle of it. Moreover, there are significant quality differences between the patents granted in developing versus developed countries which will also affect the quality of subsequent spillovers. Secondly, for transition countries these effects are exacerbated by a volatile patenting output over time and a decreasing ratio of foreign to domestic patenting in the 1990s. However, in terms of licensing, the effects on productivity are greater for transition economies than otherwise, signaling that the technological investments made by firms yield important benefits, which are visible even at the macro level. Finally, Models 7-9 include all postulated spillovers plus country fixed effects and lagged and leads of the first-differentiated regressors (not reported), despite foreseen collinearity problems given the construction of these variables. The results from separate regressions are very similar, except that the magnitude of these effects changes for FDI and technological licensing.

3.5 Robustness checks

This section checks the robustness of the results to the use of different measures of technological progress than TFP, separate estimations for each source (channel) of technology, inclusion of more control variables, and interaction effects between spillovers and main variables of interest.

3.5.1 Different measure of technical progress

While having access to technology relevant at the world frontier present countries with the possibility to utilize them towards productivity improvements, this ultimately depends on their existing absorptive capacity and technical efficiency levels. While for absorptive capacity, I have utilized a widely known and adopted proxy, namely human capital, to assess the technical efficiency level of a country I will employ a stochastic frontier analysis (SFA). The production frontier refers to the maximum output attainable under a set of given inputs. As such, countries can operate either within or on this frontier. At the national level this can been decomposed into gains from efficiency and gains from technologies [11]. For the purpose of this paper, I am interested in the latter. To technical efficiency parameters are estimated on the basis of (1) by maximum likelihood using the *frontier* command in Stata version 11.

Table 5 reports the results using the technical efficiency index obtained from the stochastic frontier analysis. The results are very similar to those using total factor productivity. The imports of goods remain the most important channel for technical efficiency gains at the country level. Patents and FDI bear similar effects in magnitude, followed by technological acquisition via licensing. The impacts for all these variables except patenting are greater in the case of transition countries than for the developed ones, suggesting that all these international interactions bear significant benefits for emerging countries in terms of growth and catching-up.

3.5.2 Separate estimations of each channel for spillovers

Considering the potential problems in estimating the concurrent spillovers via these channels, I employ also an alternative strategy by estimating them in separate regressions. Table 6 reports these estimations using sequentially the three spillover channels and technology licensing as explanatory variables for total factor productivity. Very similar results are obtained for countries' levels of technical efficiency; the results are not reported here due to space constraints but are available upon request. Overall, all these factors have robust positive effects on TFP and technical efficiency. Western economies gain through trade, FDI and patent related spillovers while transition economies benefit from trade, FDI and direct licensing of technologies. The effects of trade appear more significant in the case of developed economies, while FDI has a bigger impact in transition countries, although when analyzing technical efficiency the latter seem to have greater benefits across the board. Similar to previous estimations, patent related spillovers are significant only for Western economies while technology licensing determines productivity of transition economies.

3.5.3 Additional controls

So far, consistent with the endogenous growth theory, it has been assumed that technological progress is driven by R&D efforts (domestic and foreign) and human capital endowments. Thus to isolate the effect of spillovers in the regressions, I have employed a fixed-effects estimator. However, it is possible that other factors play a role as well, especially in emerging markets represented in this context by Central Asian and Eastern European economies. Therefore, I have added several other variables that are considered in the literature: financial development, openness (to trade, FDI and patents) and infrastructure. All these factors have been considered as important determinant of economic development in different streams of literature. Financial development reduces transaction costs, paving the way for more trade and FDI, as well as providing an easier access to credit, which translates into superior investments in capital and R&D [3,4]. Governmental policies with respect to trade, FDI and patenting affect directly the amount and composition of these flows, which in turn affects the quality and amount of potential spillovers [59]. Finally, the significance of infrastructure in the development (growth) process has been heavily documented by prior literature [79]. Good infrastructure facilitates workers mobility , reduces transaction costs and stimulates an efficient allocation of inputs, all of which result in productivity improvements. In terms of data, these indicators are drawn from the World Bank statistics: financial development data accounts liquid liabilities to GDP ratio (IFC database), infrastructure is proxied by the total telephone subscribers (fixed-line plus mobile) per 1000 inhabitants (World Development Indicators), while openness in x dimension is computed as inward plus outward flows of x over GDP, where x stands for flows of trade, FDI and patents. Again, not all results are reported here due to space constraints, however, they are available upon request. Overall, I find that the magnitude and ranks of spillovers remain similar to the previous estimations. Table 7 (Models 31 through 35) presents some of these results (in the case of trade related spillovers). Among the openness measures employed, trade and financial (FDI) aspects appear to have positive and statistically significant effects on productivity, while patent openness has a weak negative one. Financial development and existing infrastructure have positive coefficients, although the statistical significance of the latter is lower. Throughout these estimations the coefficient of the spillover variable (in this case, trade) remains positive and highly significant. Similar regressions were carried out for the rest of the postulated spillover channels and the results follow closely the conclusions enunciated so far.

3.5.4 Interaction effects

Often, following [27] the literature explores the interaction between foreign R&D spillovers and the degree of openness of an economy to cater the possibility that economies which are more open, would also benefit more in terms of capturing these spillovers. Therefore I focus on three potential interactions between spillovers and domestic R&D efforts (absorptive capacity potential), infrastructure (development level) and trade openness, all with important consequences for economic theory and policy practice. The results of this exercise in the case of trade related spillovers are reported in Table 7 (Models 36-38). They support the absorptive capacity story (positive and statistically significant coefficient for the interaction between domestic R&D stock and spillover variable) and free trade benefits (the more open a country is in can take better advantage of these spillovers).

4 Discussion, implications and conclusions

Fuelled by R&D investments and robust innovation systems that blend successfully firms, institutions and universities, productivity is seen as the main engine of economic growth and development. However, in practice, only few countries posses the financial endowments and functional systems to harness it properly. Some exceptions to this conventional wisdom includes several Asian "miracles" that managed to leap-frog towards the world's technological frontier in an impressive manner. However, most developing nations lag far behind developed nations and are increasingly dependent on foreign sources of innovation to reduce this gap. Thus, especially for these countries, identifying channels through which such transfers occur and their relative efficiency, is of great significance.

The objective of this paper was two-folded: first, to quantify and rank in importance the impact of embodied and disembodied international R&D spillovers on domestic productivity of countries; secondly, to distinguish the magnitude of these effects in different stages of development. Using a newly developed dataset that quantifies spillovers via three spillovers channels (trade, foreign direct investment and patenting) plus technological imports, I analyze their relative effectiveness across 47 transition and developed economies over a period of 19 years.

The results support all postulated channels as sources for international technological spillovers. As expected, trade remains the main distributor of foreign technological content that impacts the domestic productivity of firms via superior intermediate goods. A bit surprising, the effects are quite similar between developed and transition economies, a bit larger for the latter in some specifications, suggesting that the gains from trade in relative terms favor these group of countries, and contributing more towards their development than in the case of advanced industrialized economies. Trade is followed in magnitude by inward FDI, which has the second largest effect in terms of technical spillovers on productivity. While most FDI still occurs between developed nations, emerging markets' shares are growing at an exponential rate. Beyond the direct effects of inward FDI in terms of growth and employment, I find that these flows are also associated with large R&D spillovers via equipment, personnel and know-how that gets transferred with MNEs shifting activities. Thirdly, foreign patenting (i.e. done abroad) represents a channel through which technology diffuses to other countries. If a company needs to protect its intellectual property in a market it usually decides to apply for a local patent; subsequently, this information becomes publicly available in the local language to any other interested parties, hence opening up avenues for future local contributions in this domain. Spillovers from foreign patenting appear significant only for developed (Western) nations that have extensive patent pools, better IPR systems, and larger exchanges of FDI, all of which would encourage intense bilateral patenting. Finally, direct acquisition of foreign technologies (licensing) represents a straightforward channel to boost one's productivity, and its effects appear to be significant for transition countries, probably due to selection effects and their relative backwardness vis-a-vis to technologies they acquire, translating into significant improvements noticeable also at the aggregate level.

Overall, my results confirm trade as the main carrier of embodied technology for all countries. The estimated elasticities of imports are large under all econometric specifications and have the highest statistical significance among all spillovers computed. This finding is consistent with the classical Ricardian argument for gains from trade openness and specialization, but also with the more recent "export-led growth" story, where countries can leapfrog in the global wealth distribution by shifting their specialization to more sophisticated (and with higher technological content) goods. Such achievements are usually the result of both concerted development national agendas and decentralized efforts of local firm to learn foreign processes and reverse engineer imported products.

Both patent-related and FDI spillovers have a smaller and less robust influence on domestic productivity. In the case of the former, this is particularly important since many national agencies promote and encourage aggressively MNEs to set-up shop in developing economies aiming for better regional and national growth perspectives (e.g. export processing zones, tax incentives). These results suggest that FDI bears positive spillovers both for developed and developing nations and that on average, the benefits appear to be larger for the latter. This is consistent with the results of a recent meta-analysis by Meyer and Sinani [62] showing a non-linear relationship between the development level of a country and the amount of spillovers it receives via foreign investments. However, it is obvious that these effects are much smaller in productivity terms that those coming from trade integration.

Finally, direct imports of technologies, proxied by the stream of payments on royalties and licenses from abroad, contribute significantly to domestic TFP of transition economies. Their impact seconds that of trade and FDI related spillovers and their statistical relevance remains robust throughout estimations. This finding complements Mendi's [60] results in the case of OECD countries, providing new evidence for the importance of markets for technologies in the case of transition economies. The data shows significant outward streams of payments that increase over the 1990s in these countries signalling an intensification of technological links with various foreign partners.

From a policy perspective, these results emphasize the importance of trade relations (both in flows of goods and technologies) followed by foreign direct investment and foreign patenting. However, these effects are unevenly distributed between developed (Western) and transition (Eastern) countries, and moreover within these groups. In the case of transition economies, the friction is clear between Eastern Europeans (CEECs) and former Soviet countries (CISCs), as a result of differentials in both initial conditions and subsequent policy mixes. All else equal, the former have implemented radical reforms, opened up quickly to trade and foreign investments, and focus their economic activity to integrate within a larger Europe by joining the EU. In contrast, the latter opted for a more gradual approach that has not proved to be equally successful and are still much dependent on Russia in terms of trade and investments. Thus, improving their openness and diversifying across the economic and innovative spectrum, complemented by domestic efforts to spur and grow absorptive capabilities and reliable institutions could be key ingredients for faster development in the region.

The process of globalization has generated unprecedented liberalization of trade and proliferation of stronger intellectual property rights (IPR) regimes worldwide. These forces have contributed also to the increasing importance of rent and knowledge spillovers in determining economic productivity, especially in developing countries that do not perform much R&D on their own. This study provides empirical evidence of their effects in the case of 47 countries and assesses their relative importance suggesting that some of the "usual suspects" (i.e. FDI in developed nations) might not be as important as previously thought, while others (e.g. cross-country patenting, international licensing) have yet to be explored in depth.

However, the above results must be met with caution given the inherent methodological and data limitations, specially salient for transition countries. For example, licensing as a weight of disembodied knowledge assumes that measures a significant amount of technology transfer beyond the intra-group (parent-subsidiary) flows, often dictated by local factors (e.g. tax regimes, growth perspectives, firm strategy). Similarly, patent counts are indicative of the amount and direction of knowledge transfers but they could be further strengthened strengthened by using citation weights as a signal for quality. However, due to the limitations of the bilateral patenting data used, this is not feasible for transition economies. Thirdly, given the significant disparities in terms of R&D investments between transition and developed nations, I assume negligible spillovers from the latter to the former. Subsequent contributions may distinguish between developed-to-transition and transition-to-transition R&D spillovers to formally test this assumption. Further refinements may include sector or micro-level data on R&D capital, bilateral patenting and foreign investments can provide more insights on the issue of spillovers. Finally, valuable contributions can be made in explaining differences in adoption and absorbing foreign technologies between countries via multiple channels by exploring both sides of the equation (productivity and sources of improvements) in an exhaustive way, and test possible mediating effects that exploit both temporal and cross-sectional heterogeneity. International variations in terms of business behavior, patenting or cultural norms, all central to this line of research, may yield interesting empirical and theoretical contributions to the field.

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A Data and variable construction

A.1 Classification of countries in the dataset:

- *OECD countries*: Australia, **Austria, Belgium**, Canada, **Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy,** Japan, Korea, Mexico, **Netherlands**, New Zealand, **Norway, Portugal, Spain, Sweden, Switzerland**, Turkey, **United Kingdom**, United States of America.

- *Central and Eastern European* transition countries (CEECs): Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Macedonia, Poland, Romania, Serbia and Montenegro, Slovakia, Slovenia.

- *Commonwealth of Independent States* transition countries (CISCs): Armenia, Belarus, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russian Federation, Tajikistan, Turkmenistan, Uzbekistan, Ukraine.

In the estimation tables, I refer to *Western European countries* (wec) as all European OECD countries **bolded** above plus several small European states (Cyprus, Luxembourg, Malta), while *transition countries* (trc) include both CISCs and CEECs.

A.2 Perpetual Inventory Method (PIM)

This is a frequently employed method for converting flow variables into stocks. Suppose that the following relationship holds in a steady state situation between the steady state value (S^*) and its flow value (F^*):

$$(1+g)^{t+1}S^* = (1-\delta)(1+g)^t S^* + (1+g)^t F^* \tag{9}$$

where $t = 0, ..., T$, g represents the average growth rate of this variable in this period and δ is a constant depreciation rate. Solving for the stock value we get that $S^* = \frac{F^*}{(\delta+g)}$.

Assuming a positive growth rate over time, the expected value of stocks and flows of this variable are given by:

$$E(S_t) = (1+g)^t S^* \tag{10}$$

$$E(F_t) = (1+g)^t F^* \tag{11}$$

The initial stock value can be determined as:

$$S_0 = E(S_t) = \frac{E(F_t)}{(\delta+g)} \tag{12}$$

while subsequent stocks are assumed to depreciate linearly by δ from $t = 1, ..., T$:

$$S_t = (1-\delta)S_{t-1} + F_{t-1} \tag{13}$$

Variable	Description	Obs	Summary Statistics		Unit Root Tests			
			Mean	St.Dev	LLC	IPS	B	H
log TFP	Log Total Factor Productivity	910	2.00	0.43	20.32	-0.63	-1.97*	16.10***
Tech Eff	Technical efficiency score	816	0.70	0.21	5.75	-0.06	2.24	8.81***
log S^{TRADE}	Log Trade Spillovers	940	5.37	2.53	17.95	1.33	-0.83	11.24***
log S^{FDI}	Log FDI spillovers	933	4.17	2.95	18.01	7.20	1.46	9.68***
log S^{PAT}	Log Patent spillovers	959	1.38	1.72	4.52	1.35	2.66	12.40***
log M^{TECH}	Log Technology imports	959	7.83	9.44	6.05	0.67	1.77	17.10***
log DRD	Log domestic R&D stock	942	8.38	2.21	10.64	0.38	4.60	16.01***
log school	Log schooling years adults	959	2.20	0.24	-1.64*	0.65	12.31	18.94***
log tr_open	Log trade openness	767	5.83	0.87	-4.00***	0.21	0.98	13.50***
log FDI_open	Log FDI openness	711	3.09	1.69	-12.69***	-7.17***	-1.83*	12.77***
log pat_open	Log patent openness	470	-1.29	0.91	-6.76***	-0.03	0.00	15.10***
log financial develop	Log financial development	786	9.49	3.23	-3.89***	-1.18	0.50	3.88***
log infrastr	Log infrastructure	922	3.30	0.77	-3.39***	6.11	17.18	13.85***

Table 1: Descriptive statistics for the full sample of countries

Notes: LLC is the Levin, Lin and Chu (1992) test, IPS is the Im, Pesaran and Shin (2003) test, B and H refer to the one described by Breitung (2000) respectively Hadri (2000); LLC, IPS and B have the null of unit root; H has the opposite, namely stationarity; *, ** and *** indicate parameters that are significant at the 10%, 5% and respectively 1%

Variable	Description	Summary Statistics		
		all	*wec*	*trc*
log TFPit	Log Total Factor Productivity	1.816	2.211	1.754
		(0.533)	(0.175)	(0.744)
Tech Eff	Technical Efficiency	0.703	0.865	0.572
		(0.213)	(0.892)	(0.194)
log school	Log schooling years adult	2.204	2.126	2.196
		(0.242)	(0.183)	(0.279)
log DRD	Log domestic R&D stock	8.382	9.684	7.411
		(2.208)	(1.898)	(1.902)
log S^{TRADE}	Log Trade Spillovers	7.105	8.857	3.976
		(2.331)	(1.471)	(2.199)
log S^{FDI}	Log FDI spillovers	5.390	7.326	2.317
		(3.511)	(2.963)	(2.170)
log S^{PAT}	Log Patent spillovers	3.277	4.106	0.965
		(2.111)	(1.808)	(1.354)
log M^{TECH}	Log Technology imports	6.461	9.109	6.555
		(6.117)	(6.294)	(8.628)

Table 2: Means and standard deviations by country groups

Notes: *wec* refers to Western Europe and *trcc* are transition countries from Central Eastern and Southern Europe plus former Sovier Republics from Central Asia.

no	*variable*	1	2	3	4	5	6	7	8	9	10	11	12	13
1	log TFP	1.00												
2	Tech Eff	0.95	1.00											
3	log S^{TRADE}	0.60	0.54	1.00										
4	log S^{FDI}	0.66	0.68	0.63	1.00									
5	log S^{PAT}	0.24	0.17	0.60	0.31	1.00								
6	log M^{TECH}	0.24	0.21	0.41	0.10	0.24	1.00							
7	log DRD	0.36	0.24	0.76	0.39	0.58	0.32	1.00						
8	log school	0.21	0.17	0.30	0.07	0.25	0.30	0.25	1.00					
9	log tr_open	0.18	0.22	0.18	0.18	0.04	0.15	-0.13	0.21	1.00				
10	log FDI_open	0.15	0.18	0.17	0.17	0.14	0.13	-0.04	0.19	0.52	1.00			
11	log pat_open	0.10	0.07	0.00	-0.10	0.18	0.16	-0.06	0.16	-0.13	-0.10	1.00		
12	log financial develop	0.36	0.29	0.72	0.45	0.52	0.30	0.65	0.28	-0.01	0.06	0.02	1.00	
13	log infrastr	0.78	0.73	0.71	0.60	0.39	0.30	0.55	0.30	0.22	0.13	0.14	0.49	1.00

Table 3: Correlation matrix

Variables	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9
	all	*wec*	*trc*	*all*	*wec*	*trc*	*all*	*wec*	*trc*
S^{TRADE}	0.111***	0.032**	0.112***				0.105***	0.014**	0.102***
	[0.008]	[0.013]	[0.012]				[0.008]	[0.003]	[0.012]
S^{FDI}	0.021***	0.001	0.013**				0.017***	0.001	0.018**
	[0.005]	[0.003]	[0.005]				[0.005]	[0.003]	[0.008]
S^{PAT}				0.007	0.014***	-0.014	-0.004	0.013***	0.001
				[0.005]	[0.002]	[0.010]	[0.004]	[0.002]	[0.009]
M^{TECH}				0.009***	0.001	0.008***	0.005***	0.001	0.006***
				[0.001]	[0.001]	[0.002]	[0.001]	[0.001]	[0.002]
log DRD	0.007	0.097***	0.033	0.029**	0.113***	0.023	0.025+	0.102***	0.062***
	[0.013]	[0.013]	[0.021]	[0.014]	[0.009]	[0.025]	[0.013]	[0.012]	[0.023]
log school	0.029	-0.032	0.491***	0.885***	-0.025	1.324***	0.031	0.154***	0.309+
	[0.094]	[0.056]	[0.178]	[0.093]	[0.051]	[0.154]	[0.103]	[0.057]	[0.186]
constant	1.140***	1.198***	-0.107	-0.262	1.240***	-1.340***	1.142***	1.542***	0.067
	[0.181]	[0.106]	[0.405]	[0.194]	[0.098]	[0.380]	[0.199]	[0.114]	[0.406]
Pedroni tests									
Panel rho-stat	3.04***	6.79***	5.33***	3.68***	3.62***	0.98	1.66*	3.85***	6.02***
Panel t-stat	-2.75*	-2.54	-7.79***	0.55***	-8.32***	-5.89***	-2.01*	-1.52**	-3.14
Group t-stat	-2.73***	-0.45	-7.37***	-2.83***	-7.85***	-6.39***	-2.10**	-3.08***	-0.42
Mean VIF	1.16	1.30	1.14	1.13	1.05	1.35	1.73	1.44	1.67
N	769	316	453	797	340	457	769	316	453
R square	0.55	0.66	0.58	0.41	0.67	0.48	0.57	0.70	0.60

Table 4: Relative impact of embodied and disembodied technological spillovers on total factor productivity. Dynamic OLS estimations with one lag and one lead (1990-2009)

Notes: The dependent variable is *log TFP*; †, ** and *** indicate parameters that are significant at the 10%, 5% and respectively 1%; Standard errors are reported in parenthesis below the coefficients; All estimated models contain unreported fixed effects and use White standard errors; For the Pedroni unit root tests, the null hypothesis for both tests is no cointegration; Mean VIFs (variance inflation factors)are reported for all regressors in the estimation; *wec* refers to Western Europe while *trc* represents transition countries from Eastern Europe and Central Asia.

Variables	Model 10 *all*	Model 11 *wec*	Model 12 *trc*	Model 13 *all*	Model 14 *wec*	Model 15 *trc*	Model 16 *all*	Model 17 *wec*	Model 18 *trc*
S^{TRADE}	0.042***	0.074***	0.038***				0.039***	0.061***	0.036***
	[0.004]	[0.013]	[0.006]				[0.004]	[0.012]	[0.006]
S^{FDI}	0.006**	0.008***	0.004				0.006**	0.006**	0.005
	[0.003]	[0.003]	[0.004]				[0.003]	[0.003]	[0.004]
S^{PAT}				0.005**	0.013***	-0.006	0.005**	0.011***	-0.005
				[0.002]	[0.002]	[0.005]	[0.002]	[0.002]	[0.005]
M^{TECH}				0.003***	0.001	0.003***	0.002***	0.000	0.002***
				[0.001]	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]
log DRD	0.019***	0.029***	0.028***	-0.007	0.016**	0.038	0.013+	0.025**	-0.023
	[0.007]	[0.011]	[0.011]	[0.007]	[0.007]	[0.032]	[0.007]	[0.010]	[0.022]
log school	0.074	-0.01	0.061	0.289***	0.073+	0.314***	0.001	0.126***	0.034
	[0.046]	[0.045]	[0.084]	[0.045]	[0.044]	[0.071]	[0.050]	[0.045]	[0.087]
constant	0.428***	0.574***	0.490**	0.088	0.502***	0.185	0.543***	0.872***	0.514***
	[0.093]	[0.086]	[0.194]	[0.092]	[0.083]	[0.175]	[0.100]	[0.091]	[0.195]
Pedroni tests									
Panel rho-stat	5.03*	2.67	3.72	3.75	0.12*	3.23	4.91	3.99*	3.41
Panel t-stat	-4.26***	2.93*	-3.64***	-6.53***	-7.40***	-4.20***	-2.30**	-3.36***	-2.74***
Group t-stat	-7.44***	-3.10***	-7.37***	-8.88***	-4.61***	-7.73***	-4.97***	-3.30***	-4.00***
Mean VIF	1.16	1.30	1.14	1.13	1.05	1.35	1.73	1.44	1.67
N	677	276	401	705	300	405	677	276	401
R square	0.50	0.45	0.54	0.41	0.43	0.48	0.52	0.55	0.55

Table 5: Relative impact of embodied and disembodied technological spillovers on technical efficiency. Dynamic OLS estimations with one lag and one lead (1990-2009)

Notes: The dependent variable is *Tech Eff*; †, ** and *** indicate parameters that are significant at the 10%, 5% and respectively 1%; Standard errors are reported in parenthesis below the coefficients; All estimated models contain unreported fixed effects and use White standard errors; For the Pedroni unit root tests, the null hypothesis for both tests is no cointegration; Mean VIFs (variance inflation factors)are reported for all regressors in the estimation; *wec* refers to Western Europe while *trc* represents transition countries from Eastern Europe and Central Asia.

Variables	Model 19	Model 20	Model 21	Model 22	Model 23	Model 24	Model 25	Model 26	Model 27	Model 28	Model 29	Model 30
	all	*all*	*all*	*all*	*wec*	*wec*	*wec*	*wec*	*trc*	*trc*	*trc*	*trc*
S^{TRADE}	0.017***				0.088***				0.011***			
	[0.003]				[0.012]				[0.003]			
S^{FDI}		0.012***				0.007**				0.009**		
		[0.003]				[0.003]				[0.004]		
S^{PAT}			0.006***				0.011***				0.000	
			[0.002]				[0.002]				[0.004]	
M^{TECH}				0.003***				0.001				0.002***
				[0.001]				[0.001]				[0.001]
log DRD	0.011+	0.025***	0.017***	0.008	0.020**	0.017+	0.017**	0.021***	0.041***	0.047***	0.048***	0.034***
	[0.007]	[0.007]	[0.007]	[0.007]	[0.009]	[0.009]	[0.007]	[0.008]	[0.011]	[0.011]	[0.012]	[0.011]
log school	0.307***	0.327***	0.376***	0.347***	0.02	0.168***	0.098**	0.227***	0.260***	0.286***	0.374***	0.287***
	[0.042]	[0.042]	[0.042]	[0.039]	[0.045]	[0.041]	[0.043]	[0.041]	[0.075]	[0.074]	[0.067]	[0.067]
constant	0.024	0.13	0.003	-0.021	0.377***	0.271***	0.453***	0.137+	0.289	0.302	0.134	0.213
	[0.084]	[0.096]	[0.092]	[0.082]	[0.069]	[0.081]	[0.081]	[0.071]	[0.183]	[0.193]	[0.176]	[0.173]
Pedroni tests												
Panel rho-stat	1.28	3.21	2.81	2.43	-1.27*	-1.42**	-1.85**	1.48	1.42	2.88	2.71	1.89
Panel t-stat	-12.11***	-10.33***	-7.50***	-6.73***	-9.19***	-9.30***	-10.55***	-0.63	-8.85***	-6.83***	-4.38***	-2.21**
Group t-stat	-11.10***	-8.09***	-9.03***	-5.48***	-5.00***	-3.37***	-5.07***	-0.77	-10.34***	-8.01***	-7.57***	-6.44***
Mean VIF	1.10	1.00	1.07	1.09	1.04	1.10	1.05	1.02	1.21	1.00	1.10	1.20
N	705	684	705	705	300	282	300	300	405	402	405	405
R square	0.41	0.40	0.38	0.40	0.46	0.32	0.41	0.32	0.48	0.47	0.46	0.48

Table 6: Single spillover estimations on total factor productivity. Dynamic OLS estimations with one lag and one lead (1990-2009)

Notes: The dependent variable is *log TFP*; †, ** and *** indicate parameters that are significant at the 10%, 5% and respectively 1%; Standard errors are reported in parenthesis below the coefficients; All estimated models contain unreported fixed effects and use White standard errors; For the Pedroni unit root tests, the null hypothesis for both tests is no cointegration; Mean VIFs (variance inflation factors)are reported for all regressors in the estimation; *wec* refers to Western Europe while *trc* represents transition countries from Eastern Europe and Central Asia.

Variables	Model 31	Model 32	Model 33	Model 34	Model 35	Model 36	Model 37	Model 38
	all	*all*	*all*	*all*	*all*	*all*	*all*	*all*
S^{TRADE}	0.130***	0.162***	0.138***	0.066***	0.045***	0.002	0.027+	0.059***
	[0.011]	[0.011]	[0.016]	[0.005]	[0.005]	[0.009]	[0.015]	[0.017]
log DRD	0.074***	0.056***	-0.032	-0.004	-0.004	0.031***	-0.005	0.006
	[0.014]	[0.014]	[0.020]	[0.007]	[0.006]	[0.007]	[0.006]	[0.007]
log school	-0.048	-0.214**	0.053	0.064	0.083+	0.071	-0.105+	-0.143**
	[0.091]	[0.093]	[0.126]	[0.046]	[0.043]	[0.046]	[0.060]	[0.062]
log tr_open	0.108**							
	[0.044]							
log FDI_open		0.025***						
		[0.005]						
log pat_open			-0.022+					
			[0.012]					
financial develop				0.042***				
				[0.013]				
log infrastr					0.017+			
					[0.010]			
log DRD * S^{TRADE}						0.005***		
						[0.001]		
log infrastr * S^{TRADE}							0.001	
							[0.002]	
log tr_open * S^{TRADE}								0.008***
								[0.002]
constant	0.722***	0.972***	1.329***	0.268***	0.248***	0.523***	0.688***	0.698***
	[0.177]	[0.167]	[0.212]	[0.083]	[0.084]	[0.098]	[0.121]	[0.124]
N	643	546	318	531	672	690	672	629
R square	0.55	0.67	0.72	0.57	0.49	0.48	0.50	0.50

Table 7: Additional control variables and interaction effects. Dynamic OLS estimations with one lag and one lead (1990-2009)

Notes: The dependent variable is *log TFP*; †, ** and *** indicate parameters that are significant at the 10%, 5% and respectively 1%; Standard errors are reported in parenthesis below the coefficients; All estimated models contain unreported fixed effects and use White standard errors; *wec* refers to Western Europe while *trc* represents transition countries from Eastern Europe and Central Asia.

Country	log TFP	Tech effic	log S^{TRADE}	log S^{FDI}	log S^{PAT}	log M^{TECH}	Avg spill
United Kingdom	2.31	0.96	10.57	11.46	7.33	15.71	9.79
Germany	2.11	0.75	10.88	9.89	7.39	15.46	9.39
France	2.29	0.90	10.53	9.95	6.27	14.61	8.92
Netherlands	2.21	0.87	10.18	10.93	4.38	14.60	8.50
Italy	2.23	0.86	10.14	8.45	5.42	14.12	8.00
Belgium	2.29	0.93	10.08	9.55	3.54	13.95	7.72
Spain	2.17	0.82	9.75	8.57	4.15	12.41	7.49
Switzerland	2.01	0.70	9.43	8.31	4.31		7.35
Norway	2.32	0.92	8.56	7.59	5.63	11.88	7.26
Sweden	2.17	0.85	9.24	7.86	4.57	14.01	7.22
Ireland	2.43	0.91	8.62	9.02	2.76	15.29	6.80
Austria	2.18	0.87	9.16	7.15	4.02	13.37	6.78
Finland	2.11	0.82	8.35	7.45	3.94	13.04	6.58
Denmark	2.25	0.92	8.59	7.12	3.17		6.30
Turkey	1.84	0.65	8.40	4.36	5.70		6.15
Portugal	2.26	0.89	8.38	6.37	1.93	10.18	5.56
Greece	2.10	0.86	8.15	5.10	1.13	11.39	4.79
Cyprus	2.15	0.90	6.25	4.85	2.43	9.56	4.51
Iceland	2.19	0.87	5.89	0.58	2.99	7.00	3.15
Malta	2.09	0.85	5.98	0.89	2.16		3.01
Russian Federation	1.16	0.31	8.56	6.17	6.71	11.12	7.15
Poland	1.76	0.62	8.46	6.56	5.40	12.53	6.81
Hungary	1.75	0.66	7.94	7.27	4.74	11.99	6.65
Czech Republic	1.75	0.64	8.30	6.35	4.75	11.39	6.47
Romania	1.15	0.37	7.01	3.92	3.92	10.43	4.95
Slovakia	1.76	0.63	7.03	4.36	3.33	11.14	4.91
Ukraine	0.80	0.23	6.61	3.16	4.32	12.53	4.70
Croatia	2.01	0.71	6.74	3.57	3.28	10.91	4.53
Bulgaria	2.04	0.80	6.17	3.25	4.13	10.05	4.52
Estonia	2.12	0.78	5.96	4.24	2.96	8.74	4.39
Slovenia	2.06	0.75	7.13	3.11	1.37	10.53	3.87
Latvia	2.06	0.77	5.82	3.46	2.03	7.55	3.77
Serbia	1.40	0.54	5.25	1.84	3.38		3.49
Kazakhstan	1.65	0.60	5.48	3.49	0.99	9.86	3.32
Lithuania	1.68	0.63	6.08	2.03	0.44	8.78	2.85
Uzbekistan	1.52	0.55	5.04	1.27	2.18		2.83
Azerbaijan	1.52	0.69	4.38	3.30	0.21	5.47	2.63
Bosnia Herzegovina	2.27	0.83	4.84	-0.15	3.02		2.57
Macedonia	1.55	0.61	4.95	0.73	2.02	8.50	2.57
Belarus	1.49	0.52	5.29	-0.43	2.10	8.11	2.32
Turkmenistan	0.79	0.29	3.86	1.52	0.58		1.99
Kyrgyzstan	1.10	0.48	2.89	1.83	-0.16	7.49	1.52
Moldova	0.75	0.26	3.83		0.27	6.89	1.37
Armenia	1.61	0.71	3.63	0.68	-0.41		1.30
Albania	0.93	0.51	4.29	-0.42		8.63	1.29
Georgia	1.65	0.69	3.93	-0.95	0.75	8.94	1.24
Tajikistan	0.42	0.21	2.50		-0.52	5.48	0.66

Table 8: Relative magnitude of spillovers and direct technology imports (average, 1990-2009)

Note: The upper part of the table lists Western European nations plus Turkey, while the lower part includes transition countries from Eastern Europe and Central Asia. TFP is total factor productivity; Technical Efficiency is obtained from stochastic frontier productivity analysis; S^{TRADE}, S^{FDI}, S^{PAT} are computed spillovers from trade, FDI, and respectively patents; M^{TECH} represents payments and royalties for foreign technologies acquisitions