On indirect trade-related R&D spillovers: the role of the international trade network*

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Abstract

The paper aims at investigating the role that one country's position in the *international trade network* has in attracting knowledge and technology flows to it. By referring to "indirect" Research and Development (R&D) spillovers, we argue that not only is this position responsible for the number of R&D flows one country benefits from, but also for their economic impact to an extent depending on the number of trade relationships which separate it from its trade partners. This argument is developed by extending to trade-related R&D spillovers the intersectoral "Average Propagation Length" (APL) of exogenous shocks in sectoral final demand or value added. The inter-country APL of foreign R&D is then used to weight the (total factor) productivity impact of the foreign R&D stock *available* to one country, along with that of the R&D stock *produced* domestically. Different specifications of such an econometric model are estimated with respect to 21 OECD countries over the decade 1995-2005. The results are consistent with those of the models which explicitly recognize the role of indirect R&D spillovers: in particular, the TFP elasticity of the foreign R&D *available* stock is greater than that of the foreign R&D *produced* stock. The APL based results are however more robust, as they depend on the actual economic distance in trade of one country from the others, rather than, as in previous models, on the (most fitting) estimated value of its economic consequences.

Keywords: Average Propagation Length; International R&D spillovers; International trade network; Total Factor Productivity.

JEL Classification: C23; F01; O30; O47.

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[*] The three authors contributed equally to the paper and share Sections 1 and 6. Still, Section 5 could be attributed to Chiara Franco, Sections 2 and 3.1 to Sandro Montresor, Sections 3.2 and 4 to Giuseppe Vittucci Marzetti. Usual caveats apply.

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1 Introduction

The paper aims at investigating the role that one country's position in the *international trade network* has in allowing for foreign Research and Development (R&D) spillovers. Referring to the literature stimulated by Coe and Helpman (1995) on the role of trade in promoting knowledge and technology flows between trading countries – i.e. "direct" R&D spillovers – we draw on Lumenga-Neso et al. (2005) the extension according to which R&D spillovers are also "indirect", and taking place even between non-trading partners. In brief, not only does country A benefit from the R&D *produced* by its trade partner B. But also from that *available* in B because of its own trade with C, even in the absence of trade between A and C.

In the paper, we argue that this amounts to recognizing the international trade network, rather than international trade *per se*, a crucial role in conveying R&D spillovers between countries: not only is the size of international trade between countries relevant, along with that of their R&D efforts, but also the economic distance between them, in terms of direct and indirect trade relationships.[1]

This argument requires a refinement of the methodology to capture foreign R&D spillovers. On the one hand, Social Network Analysis (SNA) applied to international trade turns out inescapable in order to get an accurate account of one country's weight in both producing and intermediating knowledge flows, both directly and indirectly. On the other hand, Input-Output (IO) analysis offers some tools that, even when applied at an aggregate level – the inter-country level – are useful in building up a synthetic measurement of the "length" trade takes in "propagating" direct and indirect knowledge flows.

In the paper, we start by using SNA in an illustrative way, and rather focus on an econometric model which applies to trade-related R&D spillovers the IO idea of Average Propagation Length (APL) put forward by Dietzenbacher et al. (2005). In brief, the (weighted) average number of trade "rounds" it takes one country's produced R&D to become available in another one. A more extensive application of SNA instruments, to the more familiar IO domain of intersectoral domestic and foreign R&D spillovers will instead be postponed to our future research agenda.[2]

The remainder of the paper is organized as follows. Section 2 reviews the literature on trade-related R&D spillovers and distinguish direct from indirect foreign R&D spillovers. Section 3 develops the conceptual relationship between indirect R&D spillovers and international trade network, and suggests the use of SNA and IO to account for it. Section 4 provides the econometric model and its empirical specification, and Section 5 presents the

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[1] The geographical distance between countries is also relevant in this last respect (e.g. Keller, 2002a). However, this issue will not be addressed by the present paper, and rather put on our research agenda.

[2] On the issue see, among the others, Keller (2002b) and Bitzer and Geishecker (2006).

econometric results. Section 6 concludes.

2 Trade-related R&D spillovers: direct vs. indirect

The idea that trade enables international knowledge flows and technology transfer across countries and sectors has been elaborated theoretically and supported empirically by an extended body of literature (for a survey see, for instance, Keller, 2004; van Pottelsberghe de la Potterie, 1997).

The starting point is represented by Griliches' (1979) famous distinction between *pure knowledge* and *rent spillovers* from R&D. Rent spillovers are those which accrue to the buyer/user of a certain (capital) innovated good for the fact that such a good "embodies" new technological knowledge for which the seller/producer is unable to charge him/her (for a survey, see Jaffe, 1986). As international trade is also made up of transactions of goods, which the exporting country (or sector) can innovate before selling abroad, the importing one can benefit from foreign spillovers, as it does from domestic ones (Coe and Helpman, 1995), although possibly to a different extent.[3]

Once identified as a potential channel of international technology diffusion, trade becomes also a potential driver of economic growth for countries. In particular, in a global economy, it enables R&D to flow across countries and to improve the quality of the intermediate inputs they produce (Grossman and Helpman, 1991). Accordingly, the foreign R&D stock of a country can be expected to impact on its Total Factor Productivity (TFP) as well as its domestic one.

The issue then becomes an empirical one, in which an accurate index of the foreign R&D stock has to be worked out and its impact on TFP estimated along with that of other relevant explicative variables. This is a research stream which Coe and Helpman (1995) (CH hereafter) initiated by suggesting to equate the foreign R&D stock of a certain country to the import-weighted sum of the R&D produced in each of its trade partners. In so doing, they actually found for it a significant role in impacting on the TFP of OECD countries vs. that of domestic R&D. That work was seminal and stimulated a lot of reactions and extensions.

On the one hand, a number of papers have tried to extend the original CH setting, both by including additional explicative variables – in particular,

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[3] To be sure, the kind of trade which stimulates this foreign spillovers is mainly that of capital goods. The scanty availability of data on these trade flows, however, has led the literature to focus on trade of final goods in general. A relevant exception is represented by Xu and Wang (1999), who refer to the imports of machinery and transport equipment. While the inner mechanism is similar, a number of factors – first of all, the geographical distance – suggest to look for, and expect to find, a different impact of within-country with respect to between-country spillovers (on this crucial issue, see, for example, Eaton and Kortum, 1999; Irwin and Klenow, 1994; Keller, 2002a).

the role of human capital (Engelbrecht, 1997) and of the institutional set-up (Coe et al., 2009) – and by enlarging the dataset of the application (Madsen, 2007). In general, these extensions confirm the CH thesis of the role of trade in transmitting foreign knowledge.

On the other hand, less confirming is a thread of papers which have concentrated on the sensitivity of the CH results to the measurement of foreign R&D.[4] Along this thread, the work by Keller (1998) (simply K, hereafter) is particularly important. Not only because did he not obtain worse results than CH by weighing their foreign R&D data with random, rather than with observed trade shares.[5] But also and above all because he got an even better outcome by equating the foreign R&D of the importing country to the simple sum of the domestic one produced by its trading partners.

As Lumenga-Neso et al. (2005) (LOS hereafter) argued, rather than a supposed proof of the trade irrelevance in conveying technological knowledge, this latter application points to a different concept of foreign R&D stock, which they call *available*, rather than *produced* in a foreign country. In brief, by importing from a foreign country, not only does a domestic one benefit from the investments in R&D of the former – *direct* foreign R&D spillovers. But also from those R&D investments made by *other* foreign countries, with which the initial foreign country only has traded, while the domestic one has not – *indirect* foreign R&D spillovers.

This distinction between direct and indirect trade-related spillovers appear to us extremely interesting and appealing. As we will argue in the next section, it actually encapsulates the idea that trade-spillovers should be related to the international trade network, rather than to the simple idea of trade transactions. On the other hand, as we will also claim in the next section, such a perspective can be addressed more convincingly than LOS did.

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[4] Lichtenberg and van Pottelsberghe de la Potterie (1998) identified in CH an "aggregation-bias" due to mergers among foreign countries, and accordingly suggested to correct the original CH weighting scheme of foreign R&D by dividing the CH weights by the GDP of the exporting country. Casting doubts on the economic interpretation of that, Lumenga-Neso et al. (2005) instead suggested to refer to the GDP of the importing country.

[5] In fact, Coe and Hoffmaister (1999) replied to this test by showing how the weights he used were not truly random.

3 The implications of indirect trade-related R&D spillovers

3.1 Foreign R&D spillovers and the international trade network

Although they never used the expression "international trade network", the way LOS define the total foreign R&D stock (S_T^f) of the investigated countries, as a function of the domestic R&D capital stocks of their trade partners (S^d), is nothing but a synthetic, matrix representation of the network the countries determine by trading goods among them, both directly and indirectly. Indeed, in the following expression (Eq. (4) in their paper):

$$S_T^f = [(\mathbf{I} - \rho \mathbf{M})^{-1} - \mathbf{I}] S^d \tag{1}$$

the generic element of $\mathbf{N} = [(\mathbf{I} - \rho \mathbf{M})^{-1} - \mathbf{I}]$ – where $\mathbf{M}$ is the matrix of bilateral import shares,[6] $\mathbf{I}$ the identity matrix and ρ a parameter of absorption capacity of foreign knowledge on which we will retun later – n_{ij} stands for the share of imports country i makes from country j, both directly and indirectly: that is, through the other trade partners of i of the network which have in turn imported from j.

At first sight, referring to such an international trade network makes the analysis of foreign R&D spillovers nearly impracticable. A graphical, SNA inspection of the network constituted by the worldwide trade relationships and R&D capital stocks for the year 2000 seems to confirm this suggestion (Figure 1).[7] Apart from the expected result of a larger stock of R&D produced in the G7 countries, the only distinguishable outcome seems to be that the larger foreign R&D spillovers should be found among the G7 themselves.[8]

The LOS perspective is much more complex than the CH and the K perspectives. Extracting one node (country) from the correspondent network and comparing its indegree centrality in the different perspectives – that is, counting the number of trade flows (import/GDP) of a certain magnitude (higher than a threshold of 0.01%) which reach the country – confirms this case.

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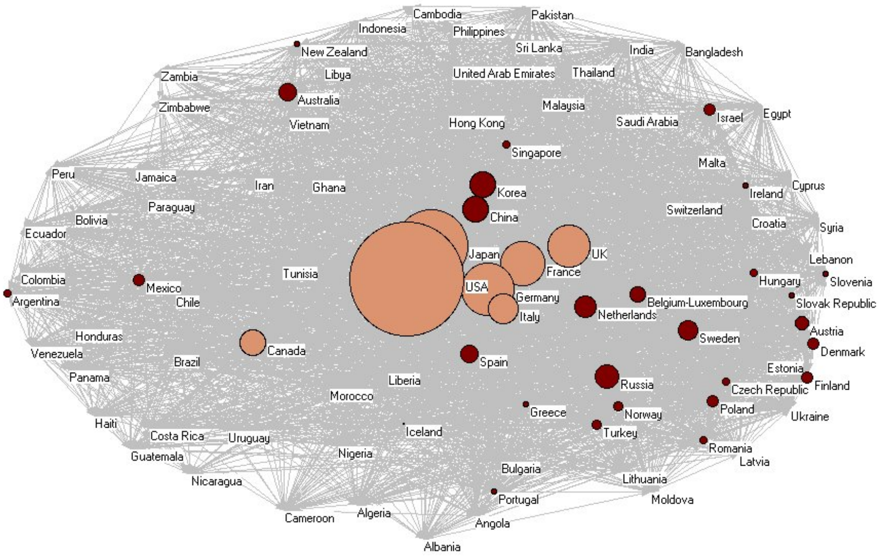
[6] Each element m_{ij} of $\mathbf{M}$ is the share of country i imports coming from country j. By definition $m_{ii} = 0$ and $\sum_j m_{ij} = 1$.

[7] For some countries, the R&D data were not available on a comparable basis. In the majority of the cases, though with some relevant exceptions (e.g. Brasil), this is due to their relatively negligible amount.

[8] Following the Fruchterman-Reingold algorithm and considering link values as a measure of similarity among nodes, in fact, closer nodes correspond to countries with larger connecting arcs. All the calculations were made using Pajek 1.23 (Batagelj et al., 2005). As the application of SNA is not the direct focus of the present paper, this and other definitions are kept at a merely intuitive level. The interest reader is referred to, among the others, Batagelj et al. (2005).



Notes – node size: R&D capital stock; edges threshold: import penetration ratio larger than 0.01% (closer nodes corresponding to countries with larger connecting arcs); G7 countries in clear.

Figure 1: LOS R&D-worldwide trade network (2000)

For instance, focusing on Japan,[9] the CH perspective would suggest that foreign R&D spillovers are channeled to it by the relatively limited number of countries from which it imports significantly (Figure 2). This makes the R&D produced by China and Korea relevant for Japan, in addition to the R&D stocks of the G7 and European countries from which Japan imports significantly. On the contrary, the imports that, for example, China and Korea receive from other countries which do not export to Japan, and that are more than numerous (Figure 1), are totally irrelevant in inducing Japanese foreign R&D spillovers.

A much more simpler network results from the K perspective, for which the Rest of the World (RoW) would simply produce and build up a total R&D "basket", which is fully *available* to Japan, irrespectively from its imports (Figure 3).

The LOS perspective stays somehow in the middle the previous two, and gets into the "black box" of the RoW by K while looking for further indirect linkages in addition to the direct CH ones.[10] In so doing, SNA becomes

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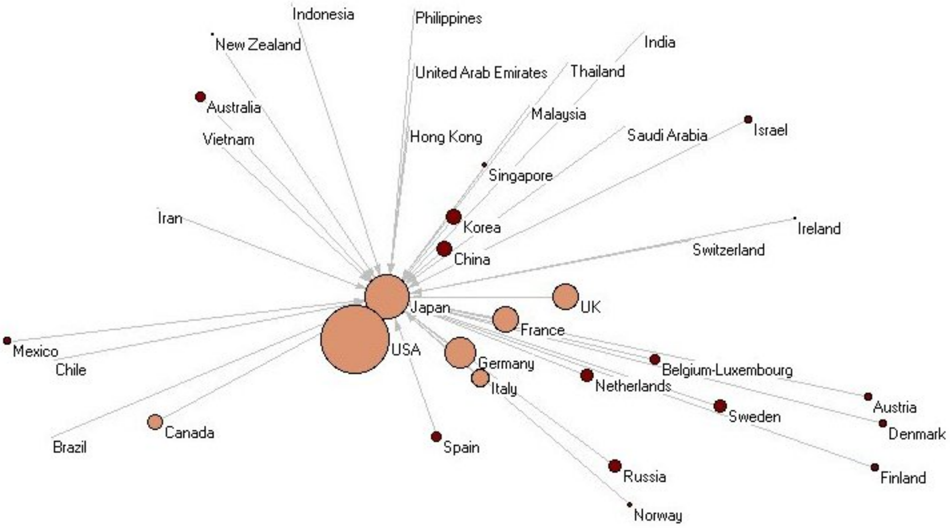
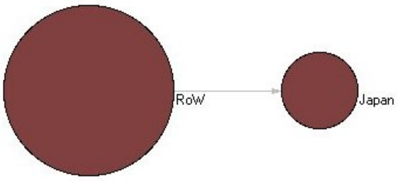
[9] Although still arbitrary, the choice has been driven by the search for a country with an average indegree centrality.

[10] To be sure, LOS argue that their own approach is able to make CH and K consistent between them.



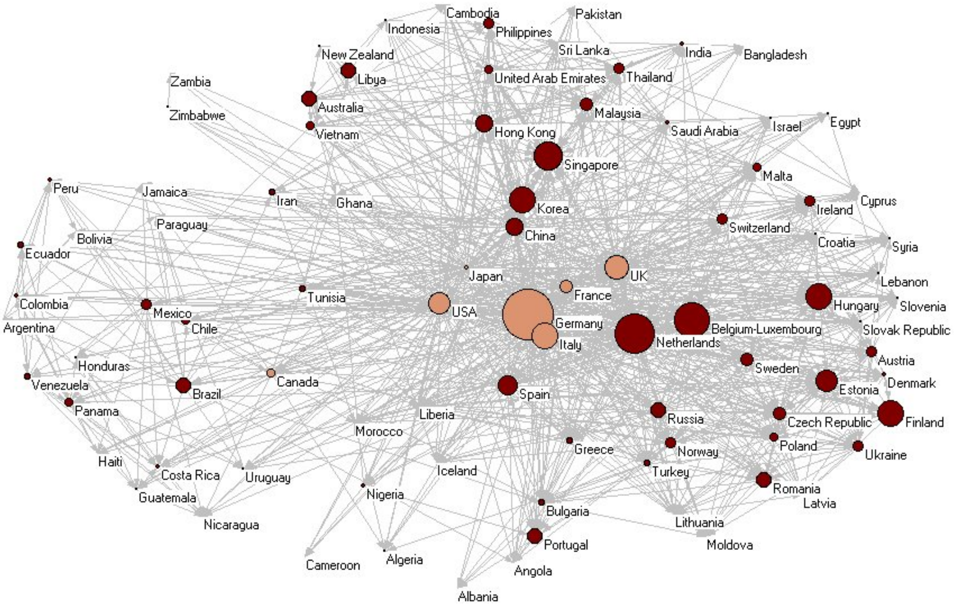
Notes – node size: R&D capital stock; edges threshold: import penetration ratio larger than 0.01%; G7 countries in clear.

Figure 2: Japan in the CH R&D-worldwide trade network (2000)



Notes – node size: R&D capital stock.

Figure 3: Japan in the Keller R&D-worldwide trade network (2000)



Notes – node size: betweenness centrality in trade flows; edges threshold: import penetration ratio larger than 0.5%; G7 countries in clear.

Figure 4: Worldwide trade network (2000)

extremely important in suggesting the actual weight that the R&D produced and available in a certain country has in stimulating R&D spillovers on the others. For example, the so called *betweenness centrality* of a country in the trade network – roughly defined as the average number of times it occurs to be on the shortest trade paths between other countries – turns out useful in detecting those countries which have a "bridging" role with respect to R&D spillovers. Although sensible to the choice of the cut-off (here set at 0.5% for the bilateral import penetration ratio), Figure 4 shows, for example, the crucial role of the Netherlands in conducing indirect R&D spillovers to the other countries. In other words, if we dropped from the network the position of this country, the stock of R&D available to the others would diminish a lot, and for Japan too. The same drop, would have been instead negligible according to the CH (Figure 2) and the K (Figure 3) perspective.

Of course, betweenness centrality is simply one of the several SNA indicators one can use. Rather than going further into the SNA implications of the foreign R&D spillovers, in the remainder of the paper we focus on what IO can do in the same respect. Without "unpackaging" the matrix representation LOS use in accounting for direct and indirect, trade related R&D spillovers, IO analysis provides us with an interesting way to retain the economic distance between countries in terms of trade relationships. A point that we will develop in the next section.

3.2 Average propagation length of foreign R&D spillovers

According to LOS, in conveying foreign R&D, direct trade linkages are attributed a different weight from indirect ones, which in turn are weighted differently according to the number of intermediate trade relationships which set in-between two trade partners. Such a weighting scheme is apparent when the $\mathbf{N}$ matrix is developed into the series of trade "rounds" through which the S^d of the foreign countries gets to the domestic one, that is (still from their Eq.(4))

$$S_T^f = [(\mathbf{I} - \rho\mathbf{M})^{-1} - \mathbf{I}]S^d = (\rho\mathbf{M} + \rho^2\mathbf{M}^2 + \rho^3\mathbf{M}^3 + ...)S^d \qquad (2)$$

In such a scheme, the R&D produced by country j (S_j^d), which reaches country i through direct imports is weighted according to ρm_{ij}; that which takes an intermediate country to the same destination, according to $\rho^2[\mathbf{M}^2]_{ij}$; that going though two intermediate countries, according to $\rho^3[\mathbf{M}^3]_{ij}$; and so on and so forth.[11]

The impact of trade intermediation on foreign R&D spillovers thus depends, also and above all, on the parameter ρ that, according to the authors, "captures the absorption capacity of foreign knowledge in the importing country" (Lumenga-Neso et al., 2005, p.1787). Following this interpretation, ρ should be defined on the domain $[0, 1]$: being $\rho = 0$ the case of no absorption capacity, and $\rho = 1$ that of perfect absorption capacity (Lumenga-Neso et al., 2005, p. 1790). Furthermore, trade intermediation would reduce the strength of the international R&D spillovers, to an extent which exponentially declines with the number of trade rounds ($\rho > \rho^2 > \rho^3 > \ldots$).

However, such a conceptual rationale does not find confirmation in the paper, where its use seems rather motivated by analytical convenience: perfect absorption capacity is actually ruled out as $\rho = 1$ would make the matrix $(\mathbf{I} - \rho\mathbf{M})$ singular and thus non invertible. First of all, ρ is not a country-specific parameter, while the different capabilities countries have of tapping into the knowledge of the others is a notorious result in the innovation literature: instead, the estimation of two different ρs, one for the most and the other for the least developed countries of their application, does not give significant results in LOS. Second, the value of ρ to be used in their TFP regressions is estimated, by looking through grid-search the value that maximizes the fitness (R^2) of the different specifications. In so doing, the conceptual boundaries of the parameter are in fact abandoned, such as when in one of the specifications the grid search gives $\rho > 1$.[12] Last, but not

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[11] $[\mathbf{M}^k]_{ij}$ is the generic element of the matrix $\mathbf{M}^k$, which is different from m_{ij}^k.

[12] While such a case allows for the theoretical possibility that trade intermediation increases, rather than decreasing the strength of foreign R&D spillovers ($\rho < \rho^2 < \rho^3 < \ldots$),

least, a closer inspection of Eq. 2 would seem to suggest that, rather than (or in addition to) the absorptive capacity of one country, ρ stands for a sort of decay rate foreign R&D spillovers are subject to while passing (though instantaneously) from one country to another: an issue that, rather than on country-specific elements, would actually depend on its position in the international trade network.

Given the crucial role of ρ, these flaws in its definition appear to us particularly serious and stimulate the search of an alternative weighting scheme. In looking for it, we found that the notion of *Average Propagation Length* (APL), developed by Dietzenbacher et al. (2005) (DRB hereafter) to measure the economic distance between sectors could actually fit our case of an economic distance *between countries* (see also Dietzenbacher and Romero (2007)).

The stepwise manner LOS address the direct and indirect import requirements of a certain country is actually conceptually identical to the way standard IO analysis deals with the effects of a demand pull occurring in sector j ($\Delta\mathbf{f}$) on the total sectoral output of i ($\Delta\mathbf{x}$). By neglecting the round-zero effects – amounting to the initial demand-led increase of output ($\Delta\mathbf{x} = \Delta\mathbf{f}$) – the direct and indirect effects of $\Delta\mathbf{f}$ on $\mathbf{x}$ in the subsequent rounds, that is the inputs needed to produce $\Delta\mathbf{f}$ (round 1), the inputs for these latter inputs (round 2), and so forth, can be written as:[13]

$$\Delta\mathbf{x} = (\mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + ...)\Delta\mathbf{f} \tag{3}$$

where $\mathbf{A}$ is the input coefficient matrix, whose generic element is defined as $a_{ij} = x_{ij}/x_j$ – where x_{ij} are the input deliveries of sector i to sector j and x_j the total output of the latter.

Mutatis mutandis, in an inter-country world, this is conceptually similar to the effects that an increase of the R&D produced in a certain foreign country (ΔS^d) has on the R&D stock available in another domestic country through trade (ΔS^f_T):

$$\Delta S^f_T = (\mathbf{M} + \mathbf{M}^2 + \mathbf{M}^3 + ...)\Delta S^d \tag{4}$$

which is precisely the definition of S^f_T put forward by LOS (Eq. (2)) once the matrix $\mathbf{M}$ gets transformed in order to make the use of ρ analytically unnecessary.[14]

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for example by developing super-additive synergies through countries' interactions, on the other hand, it is inconsistent with the idea of absorptive capacity *per se*: how could country i absorb more than the R&D available in country j?

[13] As we will see, the round-zero effects can be taken as correspondent to the domestic R&D stock of a certain country in LOS, and are thus not relevant in the analogy.

[14] Indeed, if we take the suggestion by LOS themselves and redefine $\mathbf{M}$ in terms of country-by-country import penetration ratios, even a $\rho = 1$ makes the relevant matrix invertible, with no problem of singularity: the generic element of $\mathbf{M}$, m_{ij}, is therefore the

Having established such an analytical parallel, we can fruitfully pursue it and extend to direct and indirect inter-country linkages of trade-embodied R&D flows the matrix of Average Propagation Lengths ($\mathbf{V}$) DRB have defined with respect to direct and indirect intersectoral production flows between sectors. In the standard Leontief model, $\Delta\mathbf{x} = \mathbf{L}\Delta\mathbf{f}$ (with $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$), the generic element of this matrix (v_{ij}) is an average of the different (and infinite) production rounds linking sector i to sector j – i.e. round $1, 2, \ldots$ – which weighs each round according to the share of the correspondent total effect on output (l_{ij}) conveyed in it, that is: the share a_{ij}/l_{ij}, in round 1; the share $[\mathbf{A}^2]_{ij}/l_{ij}$, in round 2; and so on.

By dropping the round 0 effects, which are independent from the industrial structure, and referring to $l_{ij} - \delta_{ij}$ (where δ_{ij} is the Kronecker delta)[15] rather than to l_{ij}, the generic element of the APL matrix $\mathbf{V}$ can be defined as:

$$v_{ij} = \frac{1a_{ij} + 2[\mathbf{A}^2]_{ij} + 3[\mathbf{A}^3]_{ij} + ...}{l_{ij} - \delta_{ij}} \tag{5}$$

After some matrix algebra, the previous expression can be re-written as:

$$v_{ij} = \frac{h_{ij}}{l_{ij} - \delta_{ij}} \tag{6}$$

where h_{ij} is the generic element of the matrix $\mathbf{H} = \mathbf{L}(\mathbf{L} - \mathbf{I})$.[16]

Extending this idea of APL to the case of indirect foreign R&D spillovers, v^*_{ij} (where the star refers to our inter-country perspective) can be meant as the average number of steps (i.e. trade relationships) it takes the R&D of a foreign country j (S^d_j) to affect the stock of R&D available to a domestic country i through trade ($S^f_{T,i}$). By extending the previous analytical procedure, v^*_{ij} can be defined as:[17]

$$v^*_{ij} = \frac{1m_{ij} + 2[\mathbf{M}^2]_{ij} + 3[\mathbf{M}^3]_{ij} + ...}{l^*_{ij} - \delta_{ij}} = \frac{h^*_{ij}}{l^*_{ij} - \delta_{ij}} \tag{7}$$

where l^*_{ij} is a generic element of $\mathbf{L}^*$:

$$\mathbf{L}^* = (\mathbf{I} - \mathbf{M})^{-1} \tag{8}$$

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share of i's imports from j of the domestic output of country i. Moreover, as noted by LOS, this way we can also correct for the "aggregation bias" of the weighting scheme of CH, a problem underlined by Lichtenberg and van Pottelsberghe de la Potterie (1998).

[15] $\delta_{ij} = 1$ if $i = j$, and 0 otherwise.

[16] As DRB shows, APL is the same in a cost-push IO model, where it measures the weighted average number of steps it takes a cost-push in industry i to affect the price of product j.

[17] Let us note that in $\mathbf{M}$ the generic element m_{ij} records the import flow from j to i (over the GDP of i), whereas in the matrix $\mathbf{A}$ the element a_{ij} is the unit flow of inputs from i to j. Therefore, for consistency, we must use the transpose of $\mathbf{M}$ and then transpose the result accordingly.

and h^*_{ij} the generic element of $\mathbf{H}^*$:

$$\mathbf{H}^* = (\mathbf{L}^* - \mathbf{I})\mathbf{L}^* \tag{9}$$

Once defined as in Eq. 7, the elements of $\mathbf{V}^*$ can be conceived as proxies of the "economic distance" between countries in the international trade network and thus used to weigh the R&D produced in the foreign countries in order to obtain the foreign R&D stock available to a domestic one.[18]

Such a weighting scheme has a number of advantages when compared with that proposed by LOS. First of all, it is more explicit than that of absorptive capacity in accounting for the decay rate of international R&D spillovers due to intermediation in trade.[19]

Second, unlike that based on ρ, which results bilateral as a consequence of its combination with direct and indirect import coefficients – that is through its pre-multiplication by $\mathbf{M}$, $\mathbf{M}^2$, $\mathbf{M}^3$, ... and so on – the APL weighting scheme is bilateral by definition.

Last, but not least, the same weighting scheme is calculated, rather than estimated or searched for, and then actually the outcome of the structural, latent characteristics of the data about the international trade network itself, rather than of the stochastic properties of the latter in inducing R&D spillovers and in affecting TFP.

In the light of these advantages, our expectations are that the APL weighting scheme we propose perform at least as well as the traditional ones in the research context in which trade-related, R&D spillovers have been put forward: that is, in accounting for the TFP of the domestic country. Without getting into the conceptual discussion of such TFP models, in the next sections we will try to see if this is actually the case.

4 Empirical specification

Consistently with the literature on the issue (Section 2), in order to capture the effect of foreign R&D spillovers on domestic TFP, we use the following, log-linear form:

$$\log TFP_{c,t} = \alpha_c + \beta^d \log S^d_{c,t} + \beta^f \log S^f_{c,t} + \epsilon_{c,t} \tag{10}$$

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[18] Let us note however that, unlike geographical distance, for the economic distance the commutative property does not hold, cause in general $v^*_{ij} \neq v^*_{ji}$.

[19] Indeed, the APL traces the "economic miles" which are in between country i and country j, rather than the share of R&D spillovers which could be estimated to be able to drive trough them. Following and extending Keller (2002a), one could argue that, the higher the economic, rather than geographical, distance k between country i and country j, the higher the possibility that the R&D developed by j is overtaken in its physical outcomes by that of closer countries, or by the domestic one. In this vein, the expected impact of a higher APL between two countries would be that of a lower impact of the R&D produced by the latter on that available to the former, and of its impact on the relative TFP.

where $TFP_{c,t}$ is the Total Factor Productivity of country c at time t, α_c a country dummy, $S^d_{c,t}$ the domestic R&D capital stock, S^f the foreign R&D stock and $\epsilon_{c,t}$ an error term.

By referring to LOS, CH and K (in this same order), we estimate five specifications of Eq. (10), plus a sixth one in which we introduce our own (FMV) APL-based notion of the foreign R&D stock.

In the first specification, as in LOS, we calculate the total foreign R&D stock (S^f_{LOS}) according to Eq. (1) by using an estimated value of ρ. In particular, S^f_{LOS} is generated for different values of ρ, starting from 0 and increasing it by discrete changes of 0.005, up to 0.999. The actual ρ is then chosen at the value which maximizes the overall fitness of the regression (R^2).

In the second specification, as also done by LOS, we calculate the total foreign R&D stock (S^f_{LOS2}), still according to Eq. (1), but by defining $\mathbf{M}$ as the matrix of bilateral import penetration ratios.[20] The parameter ρ is again estimated by means of a grid search, now searching in a larger range and allowing for the possibility that it can in fact be greater than 1.[21]

In the third and fourth specifications, we replicate CH. In particular, in the third specification we estimate Eq. (10) by constructing the foreign R&D stock as $S^f_{CH} = \mathbf{M}S^d$, where $\mathbf{M}$ is the matrix of bilateral imports over each and every country's total imports.

In the fourth specification, we instead estimate the alternative specification of CH:

$$\log TFP_{c,t} = \alpha_c + \beta^d \log S^d_{c,t} + \beta^{dG7} G7 \cdot \log S^d_{c,t} + \beta^f \omega_{c,t} \log S^f_{CH\ c,t} + \epsilon_{c,t} \quad (11)$$

where $\omega_{c,t}$ is the share of country c's imports on its GDP and $G7$ is a dummy that takes value 1 for the countries belonging to the G7.

In the fifth specification, following K, we estimate Eq. (1) defining the foreign R&D stock of each and every country (S^f_K) as the simple sum of the correspondent Rest of the World's R&D stock.

Finally, in the sixth specification, we estimate Eq. (1) by building up the foreign R&D stock on the basis of the APL idea. In particular, relying on the discussion of Section 3.2, we assume that, the larger the economic distance between countries, the smaller the R&D spillovers conveyed by total trade flows among them, and thus consistently use the following weighting scheme:

$$\mathbf{W} = [w_{ij}] = \left[\frac{l^*_{ij} - \delta_{ij}}{v^*_{ij}} \right]$$

where l^*_{ij} is the generic element of the matrix $\mathbf{L}^*$ (Eq. (8)), δ_{ij} the Kronecker delta and v^*_{ij} the APL between j and i. In brief, we refer to our own (FMV)

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[20] Therefore, m_{ij} measures country i's imports from country j over the GDP of i.

[21] ρ is chosen in the range $[0, 3]$, with $\Delta\rho = 0.005$, as enlarging the set further would have produced negative estimates of the foreign stock.

account of the foreign R&D stock, defined as:[22]

$$S^f_{FMV} = \mathbf{W} S^d$$

We estimate all the six specifications over the period 1995-2005 for 20 countries. Although not very long, once compared with other works in the same literature, such a temporal span is simultaneously the longest and the most updated one can refer to by relying on officially available data (for a discussion of the dataset, see Appendix A), and for which data inaccuracy is thus minimized.

Following CH, and unlike LOS, we do not lag the stock of foreign R&D. First, because we found no evidence of endogeneity of R&D stocks;[23] second, because the different lag time needed in equilibrium for the foreign R&d stocks to affect TFP are already captured by the APL in our specification.

Finally, as homoskedasticity and zero serial correlation are firmly rejected by the tests, in order to account for the presence of first-order panel-specific autocorrelation and panel heteroscedasticity we estimate the models also using a Feasible Generalised Least Square (FGLS) estimator.

5 Econometric results

Table 1 reports the estimation results of the six different specifications, carried out by using, alternatively, the Fixed Effects (FE) model, the Random Effects (RE) model and the Feasible Generalised Least Square (FGLS) estimator. However, because of the first order serial correlation (Wooldridge test) and groupwise heteroskedasticity (Breusch-Pagan test) of the residuals, in what follows we will mainly discuss the estimates of the FGLS estimator.

At the outset, we should notice that, once replicated with respect to our most recent period, 1995-2005, the estimated TFP elasticities of the R&D capital stocks, both foreign and domestic, are lower than those obtained by CH, LOS and K for the period 1971-1990, and this holds true across all the different specifications and models. This would seem to suggest that, entering

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[22] We also allowed for a more flexible form. In particular, we tried the following specification:

$$\mathbf{W} = [w_{ij}] = \left[(v^*_{ij})^\gamma (l^*_{ij} - \delta_{ij})\right]$$

and performed a grid search along the lines of LOS to find the value of γ maximizing the fitness of the regression. We did this also in order to have some insights on the hypothesis of a negative effect of the economic distance between countries on total R&D spillovers ($\gamma < 0$) vs. the alternative hypothesis of a positive effect, because of synergies or other super-additive factors ($\gamma > 0$). The grid search was performed from $\gamma = -5$ up to $\gamma = 5$ ($\Delta\gamma = 0.005$) and returned a value $\gamma^* = -0.145$, thus providing support for the hypothesis that an increasing APL makes spillovers decrease.

[23] All the different specifications have been estimated also using lagged values for foreign and/or domestic R&D stocks, and the Hausman test never rejects the null hypothesis of no endogeneity. Results are available from the authors on request.

the most recent stage of the globalisation era, the "'externalities" of R&D investments have decreased, both within and across countries: a result that, while apparently counterintuitive, is worthwhile investigating by controlling for other explicatory variables and, in particular, for the institutional changes (e.g. the IPR strength) occurred recently (Coe et al., 2009, e.g.).

Another important initial insight emerges by noticing that, over the 1995-2005 period, the estimates with the worst fit among the six specifications are the two given by CH and LOS (columns (i) and (iii)), which link the strength of the foreign R&D spillovers to the simple *composition* of one (domestic) country's import flows (e.g. to its bilateral/total imports ratio). Moreover, in these same specifications, the coefficients turn out to be all insignificant (though in CH the elasticity of S^d is significant at the 10% level). From a methodological point of view, this seems to suggest that, as Lumenga-Neso et al. (2005) argue (p.1789), what matters more in measuring the impact of technology embodied in imports on TFP is the *intensity*, rather than the composition of bilateral imports: that is, the extent to which such bilateral imports count on the GDP of the domestic country.

As for the other four specifications (LOS2, CH2, K, and FMV), the parameter of interest is the TFP elasticity of the foreign R&D stock, which is in fact the regressor that mostly differentiate them. Referring to FGLS, the point estimates of the correspondent coefficient range from .0083 in CH2 to .0942 in K, whereas those attached to the domestic R&D stock range from .0056 in K to .0266 in CH2. Above all, the specifications with the highest fitness are those in-between, provided by LOS2 and FMV, where the point estimates of the $\log S^f$ coefficient are around .04 and those of $\log S^d$ around .013. This is an extremely interesting result. While considering *direct trade flows exclusively*, though related to the GDP of the importing country – that is CH2 – underestimates (overestimates) the productivity impact of foreign (domestic) R&D spillovers, retaining *direct and indirect trade flows indistinguishably* – as in K – overestimates (underestimates) the same impact. Indirect trade flows should thus be retained, but appropriately: a result that is not completely new, as it somehow confirms the rationale of Lumenga-Neso et al.'s (2005) perspective.

In this last respect, let us notice that, in the estimates carried out with the first and the second specification by LOS (columns (i) and (ii)), the grid search for the most fitting ρ returns a value of 0.65 and 0.895, respectively. That is, in both cases a lower than 1 value which apparently supports their interpretation of an imperfect absorptive capacity of foreign R&D by the domestic countries. On the other hand, however, allowing for asymmetric deviations from the most fitting ρ value, in order to account for its variability between countries or groups of countries (e.g. developed and developing countries), does not improve the fitness, in any case and regardless of the direction of the asymmetry. As its country invariability was also found by Lumenga-Neso et al. (2005) themselves, and gets here confirmed, looking at ρ in terms of an absorptive capacity which is instead extremely variable across countries appears to us misleading. Indeed, as we argued in Section 3, the ρ parameter rather accounts for the rate at which the productivity impact of foreign technological knowledge decays with the increase of the economic distance (i.e. trade rounds) among countries.

This is the rationale of our own specification (MFV), which accordingly introduces in the model an "objective" measure of the economic distance between countries such as the APL. In terms of FGLS, its estimation provides results which are close to the ones of the LOS2 model, which are in turn in between CH2 and K. On the one hand, this was expected and actually confirms our interpretation: in fact, while the ρ of LOS2 can be interpreted as the decay rate of knowledge during its "economic" international diffusion, the APL of the MFV model can be seen as the prime reason of such a decay, and thus necessarily consistent with the former. On the other hand, however, there is a fundamental difference between our specification and the ones by LOS. While in LOS the effects of the indirect nature of the R&D spillovers are captured through an extra parameter, that is ρ, which is estimated and chosen in order to maximize the fitness, in MFV the prime cause of indirect R&D spillovers is calculated and enters directly in their own definitions. Because of that, both in the TFP analysis and in other contexts, our approach can be deemed to provide more precise estimates.[24]

6 Concluding remarks

Lumenga-Neso et al. (2005) argued that, by importing from a foreign country, not only does a domestic one benefit from the R&D investments of the former – that is, from *direct* foreign R&D spillovers. But also from the R&D investments made by other foreign countries, with which the initial foreign country only has traded, while the domestic one has not – that is, *indirect* foreign R&D spillovers. Building on their approach, we incorporated in it a different weighting scheme for the same spillovers, which better accounts for the role of one country's position in the international trade network. More precisely, drawing on and extending the Dietzenbacher and Romero's (2007) notion of Average Propagation Length (APL), we defined the foreign R&D capital stock *available* to a certain country by measuring the average length trade takes in "propagating" direct and indirect knowledge flows across countries: that is, the average number of steps (i.e. trade relationships) it takes the R&D of a foreign country j to affect the stock of R&D available to a domestic country i through trade. Finally, by referring to the decay

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[24] As a matter of fact, the "real" standard errors of the coefficients in the LOS1 and LOS2 specifications should be retained much higher than those reported. Indeed, the latter do not properly take into account that all the estimates rely on another parameter which is estimated from the data and enters in the equation in a quite complex way.

Table 1: Total factor productivity estimation results (pooled data 1995-2005 for 20 countries, 219 observations)

	FE estimator[a]						RE estimator[b]						FGLS estimator[c]					
	LOS	LOS2	CH	CH2	K	FMV	LOS	LOS2	CH	CH2	K	FMV	LOS	LOS2	CH	CH2	K	FMV
	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(i)	(ii)	(iii)	(iv)	(v)	(vi)
$\log S^d$	.0700	.0490	.0794*	.0635	-.0263	.0560	.0034	.0161*	.0121	.0345	.0016	.0189*	-.0137	.0125**	.0219*	.0266**	.0056	.0138**
	(.0461)	(.0525)	(.0442)	(.0472)	(.1169)	(.0496)	(.0105)	(.0093)	(.0105)	(.0210)	(.0080)	(.0097)	(.0206)	(.0050)	(.0115)	(.0115)	(.0050)	(.0055)
$\log S^f_{LOS}$	.1078						.1758**						.0225					
	(.1168)						(.081)						(.0225)					
$\log S^f_{LOS2}$		.0538						.0667**						.0427***				
		(.0421)						(.0279)						(.0070)				
$\log S^f_{CH}$			.0624						.0710						.0139			
			(.1070)						(.0546)						(.0159)			
$G7 \log S^d$				.0551						-.0059						-.0034		
				(.0947)						(.0054)						(.0027)		
$\omega \log S^f_{CH}$				.0110						.0135						.0083***		
				(.0122)						(.0108)						(.0023)		
$\log S^f_K$					-.0263						.1188**						.0942***	
					(.1169)						(.0472)						(.0184)	
$\log S^f_{FMV}$						.0576						.0709**						.0437***
						(.0464)						(.0309)						(.0079)
R^2	.749	.759	.746	.755	.756	.759	.0436	.0435	.0047	.0024	.0238	.0373						
$\log L$													647.2	640.6	638.1	636.5	634.4	640.1
χ^2													1.38	39.06	4.91	20.30	28.61	32.58

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[a] Standard errors corrected for heteroskedasticity and non-parametrically for serial correlation within countries.

[b] Standard errors corrected for heteroskedasticity and non-parametrically for serial correlation within countries. The R^2 reported is the R^2-overall.

[c] GLS estimation robust to heteroskedasticity and group specific autocorrelation of order 1.

The dependent variable is $\log TFP$. Numbers in parenthesis are standard errors. Significance levels: * 10%; ** 5%; *** 1%.

rate foreign R&D could get through because of the economic, rather than geographical, distance among countries (Keller, 2002a), we assumed that the weight of foreign R&D spillovers in building up such a foreign R&D capital stock, and in driving its economic impact – such as that on the domestic TFP – is the larger, the shorter the correspondent APL.

In order to illustrate the interpretative power of this new methodology, following the model put forward by Coe and Helpman (1995) (CH), and extended by Keller (1998) (K) and Lumenga-Neso et al. (2005) (LOS), we used it in estimating the TFP impact of the foreign R&D stock available to one country, along with that of the R&D stock produced domestically. In particular, we replicated the CH, K and LOS models, in almost all their specifications, with respect to a more updated, though less extended dataset – 20 countries, over the period 1995-2005 – and compared the relative results with those obtained using the APL weighting scheme.

Our results lead us to the following conclusions. First, also once weighted with the APL between countries, the role of indirect foreign R&D spillovers is non negligible: as in LOS, the TFP elasticity of the R&D stock *available* abroad through the APL is greater than that of the R&D stock produced by direct trade partners, to which CH exclusively refer. Second, the trade intermediation measured by APL leads to a foreign R&D stock whose TFP impact is lower than that which does not discount for it, to which Keller refers. In such a way, the APL-based results are consistent with those of the models which explicitly recognize the role of indirect R&D spillovers in impacting on TFP: for example, indirect R&D spillovers make the TFP impact of the domestic R&D stock significant, but providing the incidence of imports on the GDP of the domestic country is considered in conveying foreign R&D.

Considering the nature of the APL based model that we propose, these supporting results are of utmost importance. Indeed, rather than simply supporting the conclusion reached by LOS that, especially because of indirect trade-related R&D spillovers, trade matters as a transmission mechanism of foreign knowledge, they add to it two important specifications. First, the country position in the international trade network also matters in the same transmission mechanism, as the economic distance between countries in the network impacts on the weight of these spillovers. Second, rather than estimated and thus arbitrary to a certain extent, such an economic distance can be more robustly calculated by referring to the notion of APL of foreign R&D spillovers.

As far as our future research agenda is concerned, following the more recent literature (Keller, 2002b; Bitzer and Geishecker, 2006), we will start by investigating the APL of foreign trade-related R&D spillovers at the intersectoral level. Second, we will contrast the APL based weighting scheme with other alternative schemes obtainable by applying SNA instruments to the international trade network.

A Data appendix

The database used in the paper covers 20 OECD countries (Australia, Austria, Belgium-Luxembourg, Czech Republic, Denmark, Finland, France, Germany, Hungary, Ireland, Italy, Japan, Korea, Netherlands, Portugal, Spain, Sweden, United Kingdom, United States) plus Slovenia over the decade 1995-2005.[25] It results from the matching of three different datasets.

The first one is the EU KLEMS Database (2008),[26] from which we have drawn the country TFP.

The second dataset is the IMF's Direction of Trade Statistics, from which we have obtained the value of bilateral imports (c.i.f.) in US dollars. Because, when indirect foreign R&D is considered, imports from countries not in the previous group can nevertheless convey indirect flows, as done by Lumenga-Neso et al. (2005), we built up the **M** matrix enlarging the sample and here including 90 countries. Still as in Lumenga-Neso et al. (2005), we considered two alternative ways of building **M**: in the first, the elements of the matrix are calculated as the share of bilateral imports in total imports of each country, while, in the second, we considered the share of imports on the GDP of the importing country. In the latter case, the value of the GDP in US dollars is taken from the World Development Indicators of the World Bank (WDI).

The third dataset is the OECD Main Science and Technology Indicators (2008), from which we have taken the Gross Domestic Expenditures on R&D (GERD) – valued at Purchasing Power Parities in constant 2000 US dollars – for all the OECD countries plus some non OECD ones, that is: Argentina, China, Israel, Romania, Russian Federation, Singapore and Slovenia. Following CH and LOS, missing R&D values have been made equal to 0, as in the majority of the cases they refer to countries with relatively negligible total R&D expenditure. As a consequence, out of the 90 countries of the **M** matrix, only 35 have been retained to be source of produced R&D. From these data, we calculated the correspondent R&D capital stocks by using the perpetual inventory model (Griliches, 1979; Coe and Helpman, 1995). We assumed a 5% depreciation rate, and estimated the average annual logarithmic growth of R&D expenditures by using the data for the whole period for which R&D data were available (1981-2005). 1981 was the benchmark year for the calculation of the stock for many countries in our sample.

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[25] Due to the lack of disaggregated data, we considered Belgium and Luxembourg as a single country, adding up trade data and using GDP, R&D and TFP of Belgium.

[26] See Marcel Timmer, Mary O'Mahony and Bart van Ark, *The EU KLEMS Growth and Productivity Accounts: An Overview*, University of Groningen and University of Birmingham; downloadable at `www.euklems.net`.

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