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On 'Indirect' Trade-Related R&D Spillovers*

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Abstract

An influential literature argues that trade promotes knowledge flows and technology transmission between trading partners. This literature focuses on 'direct' R&D spillovers which are related to the levels of R&D *produced* by the trading partners. In this paper we argue that 'indirect' trade-related R&D spillovers also take place between countries, even if they do not trade with each other. These 'indirect' spillovers are associated with *available* rather than with *produced* levels of R&D. Our empirical results suggest that these 'indirect' trade-related spillovers are at least as important as the 'direct' ones, and strengthen the view that trade does matter for the international transmission of R&D. They also suggest that, due to the existence of these 'indirect' effects, bilateral trade patterns are relatively less important as determinants of the level of foreign R&D spillovers acquired through trade.

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Non-Technical Summary

An influential literature argues that trade promotes knowledge flows and technology transfers between trading partners. A seminal example of this body of work is Coe and Helpman (1995; CH hereafter). They construct an index of foreign R&D in OECD countries as the import-weighted sum of the R&D produced in each of the other OECD countries. CH find a significant relationship between TFP on the one hand and domestic and foreign R&D on the other. The results on foreign R&D confirm that trade is an important mechanism through which knowledge and technological progress are transmitted across OECD countries.

Keller (1998) has cast some doubts on CH's results. He provides two sets of alternative estimates of the effects of foreign R&D on total factor productivity (TFP). First, using random trade patterns rather than the observed ones, he obtains results that are as good, or better, than those of CH. Second, using the simple sum of foreign R&D in the rest of the world as an alternative to the import-weighted definition of foreign R&D, he obtains again better results than those of CH. Keller's results cast some doubt on the relevance of trade as a transmission mechanism for foreign knowledge.

We build on CH by introducing the concept of 'indirect' trade-related R&D spillovers. This enables us to reconcile the results of CH and Keller. Our results also support the view that trade matters for the international transmission of knowledge.

What are 'indirect' trade-related R&D spillovers? Assume that country B imports from country C. Then, B obtains R&D spillovers from C. Thus, B has an *available* level of R&D which is larger than its *produced* level of R&D. Now, if A imports from B, A should obtain a level of R&D spillovers from B that is related to the *available* level of R&D in B. In other words, A could obtain R&D spillovers from C even if it does not trade with C, as long as both A and C trade with B. Note that CH only take produced (or 'direct') R&D into account. Calculations based on the *available* levels of R&D gives us a 'total' stock of foreign R&D. The 'indirect' stock of foreign R&D is the difference between the 'total' and the 'direct' stock of foreign R&D.

We further elaborate on the concept of 'direct' , 'indirect' and 'total' foreign stock of R&D by providing several examples. Keller's second definition of foreign stock of R&D (equal to the sum of other countries' produced R&D) and our definition of foreign R&D are quite close in these examples. However, the interpretations differ. Keller' s concept implies that trade does not play a role in the transmission of foreign

R&D, while our concept implies that trade plays a more important role than that assumed by CH.

What are the findings? First, 'indirect' stocks of foreign R&D are on average 2.7 times larger than 'direct' stocks, and are larger in 21 of 22 sample countries. Second, the 'total' foreign R&D stock is much more stable than the 'direct' stock, with the coefficient of variation of the former equal to .29 on average (over time) and .70 for the latter. This finding confirms that the specific trade pattern of a given country is less important than previously thought for knowledge transmission.

Third, we estimate the same TFP equations as CH and Keller (1998) but for foreign stock of R&D we use either the 'total' foreign stock or the 'direct' and 'indirect' stocks separately. We obtain better results than those of CH and Keller. This confirms the hypothesis that once 'indirect' trade-related R&D spillovers are included in the analysis, trade plays an important role in the international transmission of R&D. Also, we find that the elasticities of TFP with respect to the 'direct' and 'indirect' stocks are not significantly different from each other. Given that the foreign stock of 'indirect' R&D is 2.7 times larger than the 'direct' stock on average, the former plays a more important role in the international transmission of knowledge.

1 Introduction

An influential literature argues that trade promotes knowledge flows and technology transfers between trading partners.[1] The basic idea is that goods embody technological know-how and therefore countries can acquire foreign knowledge —say, as measured by Research and Development (R&D)— through imports (Grossman and Helpman, 1991). A seminal example of this body of work is Coe and Helpman (1995; CH hereafter). They estimate the impact of domestic and foreign R&D on total factor productivity (TFP) in OECD countries. They construct an index of foreign R&D as the import-weigthed sum of the R&D produced in each of the other OECD countries. CH find a significant relationship between TFP on the one hand and domestic and foreign R&D on the other. The results on foreign R&D confirm that trade is an important mechanism through which knowledge and technological progress are transmitted across OECD countries.[2]

Coe, Helpman and Hoffmaister (1997, CHH hereafter) extend CH to a sample of developing countries where they explore the extent to which the latter benefit from R&D performed in industrial countries. The idea is that developing countries that do little R&D can boost their domestic TFP by importing intermediate goods embodying foreign knowledge.[3] Their findings imply that developing countries benefit more from foreign R&D spillovers, the more open they are and the more skilled is their labor force.[4] While in CH, foreign R&D is constructed as a weighted average of

[1]See Nadiri (1993), for a review of the early literature. For a review of the more recent literature see Barba Navaretti and Tarr (2000). Tybout (2000) surveys the recent micro-evidence on exposure to foreign knowledge and firm behavior in developing countries.

[2]Park (1995) also studies international knowledge spillovers in the OECD, but distinguishes between public and private R&D investments.

[3]Recent micro-evidence for Colombian firms by Kraay, Soloaga and Tybout (2001) confirms the hypothesis that importing intermediates leads to quality improvements. At the industry level, Keller (2001) also provides evidence for G-7 countries at the industry level that bilateral trade flows are the main channel of transmission for the diffusion of international knowledge and its depreciation along geographic distance. Both papers found that imported intermediates rather than Foreing Direct Investment is the main transmission mechanism of foreign knwoldge.

[4]The benefits from foreign R&D spillovers are more important when a developing country's trade pattern is biased towards industrial countries exhibiting large cumulative knowledge. The authors

the domestic R&D of trading partners using bilateral import shares as weights, CHH use import shares of intermediate goods as weights.

More recently, Bayoumi, Coe and Helpman (1999) investigated how countries can boost their productivity by trading with countries with large stocks of knowledge. Their work, largely inspired by CH, considers trade patterns as the principal transmission mechanism of knowledge among countries.[5] The authors' results are not much different when foreign R&D is defined as the simple sum of rest-of-the-world R&D, rather than as a trade-weighted sum. In other words, the results on long-run growth are not particularly sensitive to whether foreign R&D is trade-related or not (p. 420).

Keller (1998) obtains basically the same result. He uses CH's data but develops alternative concepts of foreign R&D. First, calculating foreign R&D by using 'random' trade shares rather than the observed ones, he obtains results that are as good, or better, than those of CH.[6] Second, using the simple sum of produced R&D in the rest of the world as an alternative to the import-weighted definition of foreign R&D, he obtains again better results than those of CH. Keller interprets his results as casting some doubt on the relevance of trade as a transmission mechanism for foreign knowledge.

Keller (2000a) argues that the main problem with CH is the degree of aggregation. However, using industry level data for G-7 countries plus Sweden, he finds once again that 'random' import shares perform as well as actual import shares. Thus, his results at the more disaggregated level confirm the doubts about the relevance of trade as a mechanism for the transmission of international knowledge.

The results of Keller (1998, 2000a) and Bayoumi *et al.* (1999) have led us to re-

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find substantial R&D spillover elasticities from North to South (0.0428 from United States; 0.0191 from Europe).

[5]Unlike CH, they compute the stock of foreign R&D capital using a vector of bilateral manufactures imports over total manufactures imports from all industrial countries.

[6]Coe and Hoffmaister (1999) dispute Keller's (1998) findings on statistical grounds, arguing that the weights he uses are not 'truly' random, and that results with appropriate random weights are no better than those of CH. We compare our results not with Keller's random weights, but with his other measure of foreign R&D, i.e., the sum of other countries' produced R&D.

examine the work of CH in this paper. We extend CH's analysis by incorporating the concept of 'indirect' trade-related R&D spillovers. This concept enables us to reconcile the results of CH and Keller (1998), and show that doubts concerning the relevance of trade as a knowledge transmission mechanism vanish once 'indirect' trade-related R&D spillovers are included in the analysis.[7]

The remainder of the paper is organized as follows. Section 2 provides several examples to clarify the concept of 'indirect' trade-related R&D spillovers and its relation to alternative definitions of foreign R&D. Section 3 formally derives the concept of 'indirect' trade-related foreign R&D and its relationship to other definitions. Section 4 provides the empirical specification, and section 5 presents the econometric results. Section 6 concludes.

2 What are 'indirect' trade-related R&D spillovers?

The main objective of this paper is to extend the approach pioneered by CH by incorporating 'indirect' trade-related R&D spillovers. These can be explained by the following example. Take two countries, say Belgium and the Netherlands. According to CH, the share of the stock of Dutch foreign R&D associated with its imports from Belgium depends on Belgium's domestic stock of R&D and on the Belgian share in total Dutch imports. But why should the Netherlands only benefit from the domestic stock of R&D *produced* in Belgium? The essence of CH's approach is that each country benefits from foreign R&D through trade. Since Belgium trades with the US, Germany, Japan and the other OECD countries, the stock of R&D *available* to Belgium is larger than its domestically produced R&D. Consequently, by trading with Belgium, the Netherlands should benefit from Belgium's *available* stock and not only

[7]Recent research has focused on the related question of whether knowledge spillovers have a 'national' bias. Using different methodologies and data, Branstetter (2001), Keller (2000a) and Keller (2000b) show that knowledge spillovers are primarily intra-national. Keller (2000b) however argues that this bias towards intra-national spillovers has declined through time and they have become more international.

from its domestically *produced* stock of R&D.

In other words, the fact that Belgium trades with a large number of countries raises its stock of *available* knowledge above its stock of domestically *produced* knowledge. This should have additional, 'indirect', effects on the knowledge flows that the Netherlands obtains through its trade with Belgium. In fact, the Netherlands could obtain R&D spillovers from, say, the US, even if it does not trade with the US, as long as the US is one of Belgium's trading partners.

We present two additional examples to further illustrate the concept and underline some of the similarities and differences between CH, Keller (1998) and the approach followed here. First, consider a three-country world where country A imports exclusively from B, which imports only from C. According to CH, the foreign *R&D* available in A is equal to the R&D produced in B, since the import share equals 1. Keller, by taking the simple sum of foreign R&Ds, would define it as the sum of R&Ds produced in B and C. Including 'indirect' trade-related R&D spillovers in CH's definition of foreign R&D, country A also has access to country C's R&D even though it does not import from C. This is because A imports from B, which imports from C. Thus, R&D available in B, and that can be acquired by A through its imports from B, is equal to the simple sum of R&D in B and C.

In this hypothetical world, by taking the simple sum of R&D in the rest-of-the world as suggested by Keller (1998), one is capturing the 'indirect' R&D spillovers. In other words, Keller's definition of foreign R&D coincides with our definition in this case. Incidentally, in this example, the presence of 'indirect' trade-related spillovers also implies that whether B or C do more R&D is irrelevant. Once 'indirect' trade-related R&D spillovers are included in the analysis, the questions "Who do you trade with?" and "Who does the R&D?" are in this case, and in general, less important.

Second, consider a perfectly symmetric three-country world, where every country trades with every other one in equal amounts. In this world, the three definitions of foreign R&D will yield identical results (scaled by a factor). The amount of foreign

R&D in country A according to CH is given by $S_A^f = 0.5S_B^d + 0.5S_C^d$, where S_B^d and S_C^d are the amount of domestic R&D in countries B and C respectively, and 0.5 is the share of imports from each country. This is also our definition of 'direct' trade-related R&D spillovers. If we consider the simple sum of foreign R&D then $S_A^f = S_B^d + S_C^d$, as in Keller (1998). Finally, if we add 'indirect' trade-related R&D spillovers to the 'direct' spillovers obtained by CH, then foreign R&D available in A is given by: $S_A^f = 0.5(S_B^d + S_C^d) + 0.5(0.5S_B^d + 0.5S_C^d) + ... + 0.5^n(S_B^d + S_C^d) + ... = \sum_{n=1}^{\infty} 0.5^n(S_B^d + S_C^d) = S_B^d + S_C^d$, where the 'indirect' part is due to the fact that B learns from its trade with C and vice-versa.[8] Thus, Keller's definition coincides with ours. Both definitions lead to an amount of foreign R&D which is double the level obtained under CH's definition of 'direct' trade-related R&D spillovers. Since the three definitions yield identical results (scaled by a factor), econometric studies would be unable to identify the more plausible one in this case.

As these examples show, the structure of trade patterns may make it very difficult to ascertain whether trade is the source of these R&D spillovers. Part of the R&D spillovers identified as potentially unrelated to trade in previous work may in fact be 'indirect' trade-related R&D spillovers. This is examined in sections 3 and 4.

3 Capturing foreign R&D spillovers

Following CH, we define 'direct' trade-related foreign R&D as the weighted average of foreign (produced) R&D, where the weights are given by bilateral import shares:[9]

$$S_{CH}^f = \mathbf{M}S^d \tag{1}$$

[8] Recall that $\sum_{n=1}^{\infty} b^n = b/(1-b)$ if $|b| < 1$.

[9] Note that this implicitly assumes little heterogenity in terms of the effect on TFP that foreign R&D undertaken in different countries may have. For studies that explore this heterogeneity in G-7 countries see Keller (2000a, 2000b, 2001).

where S^f_{CH} is the vector of foreign R&D (each element of the vector, s^f_c, is the amount of foreign R&D in country c); and S^d is the vector of domestically produced R&D. $\mathbf{M}$ is the matrix of bilateral import shares, where each element m_{cj} is the share of country j in the total imports of country c (by definition $m_{cc} = 0$).

To capture 'indirect' trade-related foreign R&D spillovers, define total R&D available in each country, denoted S^t, as the sum of domestically produced R&D (S^d) and the import-weighted sum of foreign R&D available in each trading partner (S^f_T):

$$S^t = S^d + S^f_T = S^d + \mathbf{M}S^t \tag{2}$$

Solving (2) for the total R&D available in each country (S^t) yields:

$$S^t = (\mathbf{I} - \mathbf{M})^{-1} S^d \tag{3}$$

where $\mathbf{I}$ is the identity matrix. Note that there exists the possibility that the elements of $(\mathbf{I} - \mathbf{M})^{-1}$ be larger than one. This does not seem to make economic sense, as the R&D obtained from foreign countries should not be larger than what they actually produce. Therefore one should choose the elements of $(\mathbf{I} - \mathbf{M})^{-1}$ so that $\bar{e}_{i,j} = \min(1, e_{i,j})$. In the empirical specification, this was not necessary for the off-diagonal elements, as none of these elements in the inverse matrix was larger than one. The diagonal elements however were set equal to 1 as by construction all the elements in the diagonal of the inverted matrix are larger than one. This constraint captures the fact that domestically produced R&D cannot be 'indirectly' re-absorbed. Two points need to be made with respect to the diagonal elements. First, the diagonal elements could be larger than one if home knowledge is improved when shared with trading partners. However, this mecanism is not explictly modelled here. Second, note that none of the diagonal elements was larger than 1.3, so removing the constraint will not have much impact on the empirical results. Moreover, without constraint, the 'indirect' effects would even be larger, thereby reinforcing our results on the dominance of 'indirect' effects.

Foreign R&D (S_T^f) is then defined as the difference between total R&D and domestically produced R&D:

$$S_T^f = S^t - S^d = [(\mathbf{I} - \mathbf{M})^{-1} - \mathbf{I}]S^d = [\mathbf{M} + \mathbf{M}^2 + \mathbf{M}^3 + ...]S^d \tag{4}$$

Total foreign R&D can then be decomposed into 'direct' (CH) and 'indirect' trade-related R&D as follows:

$$S_T^f = S_{CH}^f + S_I^f \tag{5}$$

where S_I^f are 'indirect' trade-related R&D spillovers (implicitly defined in equation (5). From equations (1), (4) and (5),

$$S_I^f = [(\mathbf{I} - \mathbf{M})^{-1} - \mathbf{I} - \mathbf{M}]S^d = [\mathbf{M}^2 + \mathbf{M}^3 + ...]S^d \tag{6}$$

Alternatively, and following Keller (1998), foreign R&D can be defined as the simple sum of rest-of-the world R&D:

$$S_K^f = (\mathbf{U} - \mathbf{I})S^d \tag{7}$$

where $\mathbf{U}$ is a unit matrix, with all elements equal to one. Note that $S_K^f \geq S_T^f \geq S_{CH}^f$. To see this note that the elements of the unit matrix cannot be smaller than the corresponding elements of $(\mathbf{I} - \mathbf{M})^{-1}$, as discussed earlier (following equation 3).

Similarly, the elements of $\mathbf{M}$ cannot be larger than the elements of $(\mathbf{I}-\mathbf{M})^{-1}-\mathbf{I}$ as the latter is equal to $\mathbf{M}+\mathbf{M}^2+\mathbf{M}^3+...$

But how large are these 'indirect' trade-related R&D spillovers? From equations (1) and (6), the ratio of 'indirect' to 'direct' trade-related R&D spillovers equals $[\mathbf{M}^2+\mathbf{M}^3+....]/\mathbf{M}$. Table 1 shows that ratio for the 22 OECD countries in our sample. The values are computed at the mean of the 20 year period (1970-1990) in our sample, using the definitions of S^f_{CH} ('direct') and S^f_I from equations (1) and (6) above.

TABLE 1: *'Indirect' vs 'Direct' Foreign R&D Spillovers*

Table 1 shows that the simple average of the ratio of 'indirect' to 'direct' R&D spillovers is equal to 2.7. Thus, on average, the 'indirect' flow constitutes over 70 percent of the total trade-related foreign flow of R&D. Note also that the 'indirect' flow is larger than the 'direct' one in 21 of the 22 countries in our sample. The exception is Canada, which imports a significant share of its total trade from the United States, by far the largest producer of R&D in the sample.

More generally, the ratio of 'indirect' to 'direct' R&D spillovers also seems to vary according to country size, degree of concentration of trade, and production of R&D of trading partners. The determinants of this ratio will be examined in future work.

As argued in Section 2, one would expect the cross-country variation to be lower for total foreign R&D spillovers (S^f_T) than for direct R&D spillovers (S^f_{CH}). Table 2 reports the coefficient of variation (CV) of 'total', 'direct' and Rest-of-the-world (ROW, i.e., S^f_K) foreign R&D in our sample of 22 OECD countries from 1971 to 1990. On average the coefficient of variation for 'total' foreign R&D is equal to .29 (with a range of .23 to .33); it averages .70 for 'direct' R&D (with a range of .65 to .76), and .12 for ROW R&D (with a range of .12 to .13). As expected, 'total' R&D flows are significantly more stable across countries than 'direct' R&D flows (with 'direct' flows more than twice more volatile than 'total' R&D flows). This is due to the fact that by definition 'total' R&D flows are less dependent on a country's specific trade pattern than 'direct' R&D flows. Also, as expected, ROW R&D flows are the most stable, as by construction 20 out of 22 of its elements are common across any two countries.

Table 2: *Variation of Total and Direct foreign R&D spillovers across countries*

Keller (1998) concluded that a country's specific trade pattern may not be relevant for its access to foreign R&D. We argue here that –because of 'indirect' R&D spillovers– a country's trade pattern may be less important than previously thought. However, as is shown below, it would be wrong to conclude from this that trade does not play an important role in the international transmission of R&D.

4 Empirical specification

In order to capture the effect of foreign R&D spillovers on domestic TFP, we use the three log linear empirical specifications used by CH and Keller (1998):

$$\log F_{c,t} = \alpha_c + \beta^d \log S^d_{c,t} + \beta^f \log S^f_{c,t} + \epsilon_{c,t} \tag{8}$$

$$\log F_{c,t} = \alpha_c + \beta^d \log S^d_{c,t} + \beta^G \left(G7 \log S^d_{c,t}\right) + \beta^f \log S^f_{c,t} + \epsilon_{c,t} \tag{9}$$

$$\log F_{c,t} = \alpha_c + \beta^d \log S^d_{c,t} + \beta^G \left(G7 \log S^d_{c,t}\right) + \beta^f \log \left[T_{c,t}\, S^f_{c,t}\right] + \epsilon_{c,t} \tag{10}$$

where $F_{c,t}$ is TFP of country c at time t; α_c is a country dummy capturing country specific effects; $S^d_{c,t}$ is domestic R&D and $S^f_{c,t}$ is foreign R&D that can be constructed using any of the three definitions described in the previous section. That is $S^f = S^f_{CH}$, $S^f = S^f_K$, or $S^f = S^f_T$. Regarding the latter definition, one can decompose foreign R&D into 'direct' and 'indirect' R&D, i.e., $S^f = S^f_{CH} + S^f_I$ and empirically test for the importance of these two components. $G7$ is a dummy variable that takes the value of 1 for countries belonging to the G-7. Finally, $T_{c,t}$ is the ratio of total imports to GDP of country c, at time t. In that specification foreign R&D is computed using bilateral imports to GDP ratios rather than the share of bilateral imports over total imports. $\epsilon_{c,t}$ is an error term that is identically and independently distributed across countries and time.

The third specification differs from the final specification in CH and Keller (1998), where the import over GDP ratio appears in front of log of foreign R&D. Here, the import penetration ratio appears inside the log. This is necessary to treat 'direct' and 'indirect' R&D symmetrically. Indeed, if one keeps the import over GDP ratio outside the log, then the openess of 'indirect' trading partners is not included in the calculations of total foreign R&D. Bringing the import penetration ratio inside the log and allowing for 'indirect' trade-related foreign R&D may also allow to partially correct for the 'aggregation' bias of the weighting scheme of CH, a problem. underlined by Lichtenberg and van Pottelsberghe de la Potterie (1998). Indeed, these authors argue that CH's weighting scheme suffers from an 'aggregation' problem, as the R&D stock distribution is affected by mergers between countries. Thus, they suggest correcting the CH weighting scheme by dividing the CH's weights by the GDP of the exporting country.[10] The inclusion of 'indirect' trade-related R&D effects in the calculation of foreign R&D implicitly introduces both the GDP of the exporting and the importing country as determinants of the weights applied to rest-of-the-world R&D.

Thus, the specification in (8) decomposes the effects of R&D on TFP according to whether they are domestic or foreign. The second specification in (9) allows for a different effect of domestic R&D on the TFP of G-7 countries. The reason is that in CH and Keller (1998), domestic R&D seems to have larger effects on TFP in G-7 countries.[11] Finally, the third specification in (10) explores the possibility that more open economies (those with a larger ratio of imports to GDP) benefit more from

[10]Note that this correction solves the aggregation problem from a statistical point of view, but does not have clear economic underpinnings.

[11]In the results reported below, we also found that the contribution of domestic R&D relative to foreign R&D is larger in G-7 countries. See Barba Navaretti and Tarr (2000) for a thorough discussion of the significance of these results for developing countries.

foreign R&D.

Finally, when using 'total' foreign R&D, we also estimate the three equations by decomposing foreign R&D into its 'direct' and 'indirect' components. The reason for that is to test whether the effect of 'direct' foreign R&D is significantly different from the effect of 'indirect' trade-related foreign R&D. One may expect 'indirect' trade-related R&D to depreciate as it goes through all these indirect channels. Thus to allow for some heterogeneity on the effect of 'direct' and 'indirect' foreign R&D on domestic TFP, these are allow to enter separetely in some specifications. Note, though, that we do not use the definition implied by (5). The reason is that S^f_{CH} and S^f_I are collinear. Thus, in order to capture *pure* indirect trade-related R&D spillovers we regress S^f_I on S^f_{CH} and use the residuals as the 'indirect' trade-related R&D spillovers in this regression. This ensures orthogonality between 'direct' and 'indirect' R&D spillovers when jointly used as explanatory variables for TFP. Results using the non-corrected definition of S^f_I are within one standard deviation of the ones reported in Table 3 in the next section (and are all statistically significant at the .01 level).[12]

The data set is discussed in the appendix. To be able to compare our results with those previously obtained by CH and Keller (1998) we use the same data set (though some of the variables were obtained from different sources and needed to be defined differently as discussed in the data appendix). The panel covers twenty one OECD countries plus Israel, from 1971 to 1990.

[12] In order to allow for possible time lags for indirect effects we also lagged S^f_I. The idea is as in Branstetter's (2001) distinction between national and international spillovers, that 'indirect' trade-related R&D spillovers may take longer to affect TFP than 'direct' ones. Results reported in the next section are qualitatively robust to the introduction of contemporaneous, rather than lagged, 'indirect' trade-related knowledge spillovers. We tested for longer lags, but their statistical significance vanishes after one year.

5 Econometric results

Tables 3a to 3c report the results of the estimation of equations (8) to (10), respectively. Each column corresponds to a different definition of foreign R&D. In the first column we define foreign R&D as in CH (i.e., S^f_{CH}). The second column uses Keller's (1998) definition (i.e., S^f_K). The third and fourth columns include 'indirect' trade-related foreign R&D spillovers. The third column uses the sum of both direct and indirect spillovers, i.e., S^f_T, whereas in the fourth column we decompose S^f_T into its direct (S^f_D) and indirect components (S^f_I).

Tables 3a, 3b, 3c: *Econometric Results*

In all three tables the estimated coefficients are very similar to those in CH, Keller (1998) and Coe and Hoffmaister (1999). The foreign knowledge stocks enter in all regressions with the expected sign and are statistically significant.[13]

It is instructive to compare in Tables 3a, 3b and 3c the magnitude of the adjusted-R^2s obtained in the various regressions. Note that the order obtained with the R^2 (across the various columns) is identical to that obtained with the adjusted-R^2, so that we only refer to the latter.

In Table 3a, the order of adjusted-R^2s from smallest to largest is as follows: $CH < T < K < CH + I$. In other words, Keller's approach does better than CH and our approach when using total foreign R&D (S^f_t) but does not perform as well as our approach when direct and indirect foreign R&D are used separately.

In Table 3b, the G7 is added as a separate dummy variable. The order of adjusted-R^2s is: $CH < K < T < CH + I$. In this case, either of our approaches does better than Keller's or CH's. And the effect of the G7 domestic R&D is empirically and statistically significantly larger than for other OECD countries. We also tested whether foreign knowledge had a larger effect on TFP in the G-7 economies, but

[13]For a discussion of endogeneity and common trends see the Statistical Appendix.

results were statistically insignificant.[14]

In Table 3c, where foreign R&D is corrected for the share of imports in GDP, the order of adjusted-R^2s is: $K < CH < T < CH + I$. In this case, CH does slightly better than Keller, and either version of our approach does better than Keller or CH.[15]

Thus our approach –when using 'direct' and 'indirect' foreign R&D separately– provides the best fit across all three specifications. The best results, with highest adjusted-R^2, are obtained in Table 3b, where the adjusted-R^2 values vary from .629 for CH, to .652 for Keller, to .672 for our approach with direct and indirect foreign R&D used as separate regressors (CH+I).

As an alternative to adjusted-R^2 comparaisons, we also use two non-nested tests for the best specification within each table: i) super-model tests and ii) Davidson and MacKinnon (1981) J tests. An unfortunate feature of these tests is that, in testing whether a set of regressors is more appropriate than another, it allows rejection or acceptance of both regressors. The super-model test runs a regression using all regressors (i.e., indirect, direct and Keller's ROW definition). The best specification is given to the regressors that keep their significance, when others lose it. In our case, the super-model test yielded inconclusive results. All variables were highly significant at the 1 percent level in all three super-model regressions (one for each table).

However, the super model test suffers from obvious collinearity problems, which are corrected in the Davidson-MacKinnon J test. The Davidson-MacKinnon test runs a regression containing all the variables of a given specification and the fitted value

[14] As in CHH, we also tested whether the knowledge absorption capacity of the importing country as measured, by the stock of domestically produced R&D faciliated the absorption of foreing knowledge. Unlike in CHH results were statistically insignificant probably capturing the difference in country coverage in these papers. CHH works with a sample of more than 70 countries where differences in absorption capacities are much larger than in the OECD.

[15] This result contradicts Keller's (1998) result obtained with the same data set. The reason for this difference in results is that Keller (1998) and CH index R&D to be equal to 100 in all countries in 1985. In this paper, as in Lichtenberg and van Pottelsberghe de la Potterie (1998), Coe and Hoffmaister (1999) and Keller (2000a), the stocks of R&D are not indexed so that we can fully capture its cross-country variation.

from another specification. If the coefficient in front of the fitted value is statistically significant then we reject the hypothesis (H_0) that the given specification is the correct one. Results from the Davidson-MacKinnon test for the specifications in Table 3b are reported in Table 4. Results for the specifications in the other two tables are similar. Each entry in Table 4 gives the p-value for the rejection of the hypothesis H_O. For example, the first entry in the table, i.e., .94, indicates that we can reject with 94 percent confidence the hypothesis that CH is a better specification than Keller's (K). Results from the Davidson-MacKinnon tests indicate that all specifications dominate CH and that none dominate $CH+I$. $CH+I$ dominates all other specification though they only dominate K very weakly. Thus the results suggest that the hypothesis that trade is a relevant mechanism for the transmission of technology cannot be rejected.

TABLE 4: *Davidson-MacKinnon non nested tests*

We now compare the impact of 'direct' and 'indirect' foreign R&D. One might think that a country would be better at transferring the technology that it produced domestically than the technology acquired from others through trade. In other words, one would expect the 'direct' foreign trade-related R&D –as measured by CH– to have a stronger impact on TFP than the 'indirect' foreign trade-related R&D.

Our results indicate that effect of the 'indirect' foreign R&D is larger than the effect of the 'direct' one in two of the three regressions (see Tables 2b and 2c), though the difference between them is not significantly different from zero.[16] Thus, we cannot reject the hypothesis that the marginal impact of 'indirect' trade-related foreign R&D is as important as the marginal impact of 'direct' foreign R&D. And since the stock of 'indirect' foreign R&D is on average 2.7 times larger than the stock of 'direct' foreign R&D, our results imply that the former's contribution to TFP is larger.

[16]The Wald test, i.e., the ratio of the square of the difference in coefficients to the sum of variance, are 1.0, 0.7 and 0.1 respectively, all well below the critical value from the chi-squared distribution with 413 degrees of freedom.

To summarize, a first important result using adjusted-R^2 as a criterion is that, while the ranking of Keller's approach varies according to the regression used, going from second highest to lowest, our approach with the direct and indirect foreign R&D used separately always performs best. Second, comparing the elasticity of TFP with respect to direct and indirect foreign R&D (last column), we note that they are not statistically different. However, the contribution to TFP of 'indirect' foreign R&D is more important given that it is 2.7 times larger than 'direct' foreign R&D in our sample. Thus, not only does the introduction of 'indirect' foreign R&D improve estimation results and re-establish the importance of trade as a channel for the transmission of foreign knowledge, but the effect of 'indirect' foreign R&D is found to be dominant.

6 Concluding remarks

CH found that trade serves as a means for the international transmission of knowledge. Keller (1998) cast some doubt on whether knowledge is actually transmitted through trade. His work led us to reexamine the work of CH. We built on the approach of CH by incorporating the effects of 'indirect' trade-related foreign R&D spillovers into the analysis to capture flows of *available* rather than *produced* foreign knowledge.

Our results lead us to the following conclusions:

First, 'indirect' trade-related R&D spillovers are on average two to three times as large as 'direct' spillovers, and the same relation holds with respect to their contribution to TFP.

Second, once 'indirect' foreign R&D spillovers are introduced into the analysis, one can no longer reject the hypothesis that trade plays a crucial role as a channel for the international transmission of knowledge.

Finally, total (direct plus indirect) foreign R&D flows are significantly more stable than direct foreign R&D flows and are therefore less dependent on a country's specific trade pattern. This fact should *not* be construed to imply that trade does not matter for the international transmission of R&D. On the contrary, we found *both* a weaker dependence of a country's foreign R&D flows on its specific trade pattern *and* stronger evidence that trade matters for the international transmission of R&D.

The identification of 'indirect' trade-related R&D spillovers at the aggregate level and for a sample of OECD countries should be seen as a first step. As part of our research agenda we plan to examine the importance of 'indirect' trade-related knowledge spillovers for developing countries, where access to foreign knowledge is crucial. Second, and following the more recent literature, we will explore the importance of 'indirect' trade-related R&D spillovers at a more disaggregated level.

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Table 1: *'Indirect' versus 'Direct' Foreign R&D spillovers*[a]

Country	S_I^f / S_{CH}^f
Australia	1.50
Austria	3.76
Belux	3.55
Canada	0.61
Denmark	3.76
Finland	3.76
France	3.00
Germany	3.17
Greece	3.55
Ireland	2.33
Israel	1.86
Italy	3.00
Japan	1.13
Netherlands	2.85
New Zealand	2.23
Norway	3.76
Portugal	2.85
Spain	1.94
Sweden	3.35
Switzerland	3.35
United Kingdom	2.85
United States	1.63
Average	2.72

[a]Source: Authors' calculations. Calculated at the mean of the 1970-1990 sample for each OECD country using equations (1), (4) and (7).

Table 2: *Variation of Direct and Total Foreign R&D spillovers across countries*[a]

Year	Total (S^f_T)	Direct (S^f_{CH})	ROW (S^f_K)
1971	0.26	0.69	0.13
1972	0.27	0.70	0.13
1973	0.28	0.72	0.13
1974	0.31	0.70	0.12
1975	0.30	0.69	0.12
1976	0.31	0.72	0.12
1977	0.33	0.76	0.13
1978	0.30	0.72	0.12
1979	0.32	0.74	0.12
1980	0.32	0.70	0.12
1981	0.32	0.66	0.12
1982	0.31	0.68	0.12
1983	0.31	0.70	0.12
1984	0.31	0.71	0.12
1985	0.30	0.71	0.12
1986	0.25	0.69	0.12
1987	0.25	0.70	0.12
1988	0.23	0.67	0.12
1989	0.23	0.65	0.12
1990	0.23	0.65	0.12
Average	0.29	0.70	0.12

[a]Source: Authors' calculations. Calculated using the coefficient of variation for the sample of 22 OECD countries each year.

Table 3a: *TFP Estimation Results of Equation (7)*[a]

	CH	K	T	$CH+I$
S^d	.079	.021	.069	.069
	(8.02)	(1.68)	(7.35)	(7.29)
S^f_D	.119	.231		.079
	(7.96)	(10.37)		(5.04)
S^f_I				.061
				(6.60)
S^f_T			.102	
			(9.45)	
R^2	.609	.644	.631	.649
$R^2_{adj.}$	.587	.623	.609	.627
# Obs.	418	418	418	418

Table 3b: *TFP Estimation Results of Equation (8)*[a]

	CH	K	T	$CH+I$
S^d	.073	.028	.061	.063
	(7.81)	(2.28)	(6.70)	(7.05)
$G7*S^d$	.126	.106	.127	.128
	(6.79)	(5.76)	(7.23)	(7.35)
S^f_D	.089	.183		.047
	(6.02)	(7.99)		(3.09)
S^f_I				.062
				(7.17)
S^f_T			.086	
			(8.18)	
R^2	.651	.672	.674	.691
$R^2_{adj.}$	.629	.652	.654	.672
# Obs.	418	418	418	418

Table 3c: *TFP Estimation Results of Equation (9)*[a]

	CH	K	T	$CH+I$
S^d	.093	.088	.089	.079
	(10.25)	(7.77)	(9.50)	(7.87)
$G7*S^d$	.146	.152	.144	.137
	(7.79)	(8.19)	(7.72)	(7.32)
$T\ S^f_D$	.047	.035		.037
	(2.95)	(2.55)		(3.20)
$T\ S^f_I$				.041
				(3.12)
$T\ S^f_T$			.040	
			(3.48)	
R^2	.627	.625	.630	.636
$R^2_{adj.}$	.604	.602	.607	.613
# Obs.	418	418	418	418

[a]Within estimation. Figures in parenthesis are t-statistics.

Table 4: *The Explanatory Power of different models*[a]

H_0/H_1	CH	K	T	$CH+I$
CH		.94	.45	1.00
K	.00		.001	.001
T	.00	.00		.34
$CH+I$	.00	.00	.00	

[a]Figures are P-values of Davidson and MacKinnon tests. Tests are run for the second specification (ii), using the M matrix of trade. Results of the Davidson MacKinnon test for other specifications were similar to the ones reported for specification (ii) above. Source: Authors' calculations.

Data Appendix

The panel data set covers twenty one OECD countries plus Israel and 19 years, making a total of 418 observations. The list of countries can be found in Table 1. Data were collected for the period 1970-1990. Data on bilateral trade are CIF imports in US$ from the IMF Direction of Trade Statistics. GDP is measured at market prices (current US$), from the World Development Indicators (WDI) of the World Bank. R&D data and Total Factor Productivity (TFP) are those used in CH and Keller (1998). The estimates of business sector R&D stocks are obtained from the OECD's Main Science and Technology Indicators, except for Israel (see CH's Appendix for more information).

The elements of $\mathbf{M}$ are computed as the share of bilateral imports in total imports (and not imports from the sample). Total imports are also used to compute the import to GDP ratio. Also, as in Coe and Hoffmaister (1999), R&D is measured in levels and is not indexed as in CH and Keller (1998). This allows us to capture size effects for R&D spillovers, which are absent in CH and Keller (1998).

Statistical Appendix

There are two well-known estimation problems with the type of regressions in this paper, a part from the level of aggregation at which (8), (9) and (10) are estimated. First, the simultaneity between trade and TFP and R&D and TFP. Second, TFP and R&D trend upward over time and the existence of these common trends may partly explain the estimated correlations reported in Tables 3a to 3c.

In order to try to correct for the simultaneity bias between trade and TFP, one could follow Frankel and Romer (1999) and use as trade-weights the fitted value from a gravity-type equation for the 22 countries in our sample. However, given that bilateral imports enter as a share of total imports (or GDP in specification (10)), simultaneity between trade and TFP should not be a serious problem. In any case as shown by Frankel and Romer (1999) and Irwin and Torvo (2000), correcting for the endogeneity of trade and growth generally increases the estimated effect of trade on growth. The more serious endogeneity problem for which we provide no correction is the endogeneity of R&D with respect to TFP. Note that the problem is with domestic R&D rather than foreign R&D. However, the endogeneity bias will affect all the estimated coefficients. An alternative would be to instrument for R&D, but it is not clear which instruments to use at this level of aggregation (see Keller, 2000 for a discussion). Thus, we tried an imperfect solution consisting of using lagged domestic R&D instead of the contemporaneous domestic R&D. Results remain within one standard deviation in all three specification.

We tested for the presence of unit roots in the different variables allowing for 1 to 4 lags using Levin and Lin (1992)'s Dickey-Fuller tests for panel data. We could not reject the presence of unit roots for any of the series. However, these variables appear to be cointegrated and there are at least three cointegrating vectors as suggested by Engle-Granger and Johansen and Juselius (1990) co-integration tests. Thus, we could not reject the hypothesis of a stationary error term in any of the three specifications. In any case, to control for the presence of common trends, we undertook two alternative estimates of (9). First we add a time trend to the estimation reported in Table 3b. The coefficients of direct R&D spillovers using both the CH and Keller definition become insignificant once a time trend is added. However, the coefficient of total R&D spillovers remain significant at the .05 percent level. Similarly, 'indirect' R&D spillovers remain statistically significant when foreign R&D is decomposed into its 'direct' and 'indirect' component (direct foreign R&D spillovers becomes statistically significant in this regression). Note that all coefficients –including the ones capturing domestic R&D– are significantly smaller, as would be expected once a time trend is introduced in the presence of common trends. Second, we run the regressions in (9) using log-differences, so that common trends (but also long-run relationships) are eliminated. All foreign R&D measures and to some extent domestic R&D variables lose their statistical significance in these regressions, with the exception of 'indirect' R&D spillovers, which remains statistically significant at the .01 percent level.