Capital goods trade and R&D spillovers in the OECD

BIN XU and JIANMAO WANG
University of Florida

Abstract. In this paper the significance of capital goods trade as conduit for R&D spillovers is investigated and the impact of international R&D spillovers on OECD countries is quantitatively assessed. Capital goods trade is tested against non-capital goods trade, and knowledge embodied in trade flows is evaluated vis-à-vis R&D spillovers in disembodied form. Our estimation indicates that about half of the return on R&D investment in a G7 country spilled over to other OECD countries. Trade in capital goods was found to be a significant channel of R&D spillovers, although the majority of the R&D spillovers in the OECD were transmitted through other channels. JEL Classification: O40, F10

Le commerce des biens capitaux et les effets de retombée des dépenses de R&D dans les pays de l'OCDE. Ce mémoire examine l'importance du commerce des biens capitaux en tant que conduit pour les effets de retombée des dépenses de R&D et mesure l'impact des effets externes internationaux du R&D dans les pays de l'OCDE. On compare l'effet du commerce de biens capitaux avec celui du commerce de biens non-capitaux, et on compare les effets de la connaissance incorporée dans les flux de commerce par rapport aux effets externes quand les effets de retombée ne sont pas incorporés. Il semble que la moitié des rendements sur les investissements en R&D viennent des autres pays de l'OCDE. Il appert que le commerce de biens capitaux est un canal important des effets externes du R&D, même si le gros des effets externes de l'investissement en R&D est transmis par d'autres canaux.

1. Introduction

Our purpose in this paper is to investigate the significance of capital goods trade as

We would like to thank three anonymous referees for constructive comments and suggestions and James Adams, Chunrong Ai, Lawrence Kenny, Yikang Li, David Riker, Douglas Waldo, and participants at the 1997 North American Summer Meeting of the Econometric Society for helpful comments on previous drafts. We are grateful to van Pottelsberghe de la Potterie for providing us with some of the data and the DSRD Program of the University of Florida for financial support. All errors are our responsibility.

Canadian Journal of Economics Revue canadienne d'Economique, Vol. 32, No. 5
November / novembre 1999. Printed in Canada Imprimé au Canada

a conduit for R&D spillovers and to quantitatively assess the impact of international R&D spillovers on OECD countries.

Capital goods are often assumed to be carriers of international knowledge spillovers in open-economy innovation-driven growth models (see, e.g., Rivera-Batiz and Romer 1991; Grossman and Helpman 1991). In recent empirical studies on R&D spillovers through international trade, however, little attention is paid to distinguishing capital goods from non-capital goods. For example, Coe and Helpman's (1995; henceforth CH) investigation of R&D spillovers in OECD countries (plus Israel) is based on total imports data.

Why is it important to distinguish between capital goods and non-capital goods in measuring foreign R&D spillovers embodied in trade? We show that there are two reasons. First, capital goods have higher content of technology than non-capital goods and hence are the major carriers of R&D spillovers embodied in trade flows. To test this hypothesis we decompose total imports into capital goods imports (KM) and non-capital goods imports (NKM), and calculate KM-weighted R&D spillovers and NKM-weighted R&D spillovers. Using these two spillover variables instead of the total-imports-weighted spillover variable in CH's regressions, we find (1) the KM-weighted R&D spillover variable is statistically significant and explains more of the variation in productivity across countries than the total-imports-weighted spillover variable; (2) the NKM-weighted R&D spillover variable is statistically insignificant. These results are shown to be robust to alternative regression specifications (level versus difference) and to the use of an alternative spillover measure proposed by Lichtenberg and van Pottelsberghe de la Potterie (1998; henceforth LP).

If capital goods trade constituted a stable share of total trade, then it would do little harm to use total imports data in the construction of R&D spillovers embodied in capital goods imports. But the share of capital goods trade in total trade is volatile both across countries and over time. In our sample of twenty-one OECD countries, the KM-imports share ranges from Japan's 0.25 to Canada's 0.55 in 1990, and the standard deviation of the share is as high as 0.09 for some countries over the 1983–90 period (see table A1 in the appendix for details). Thus, the use of total imports data may produce a distorted measure of R&D spillovers embodied in capital goods trade. Keller (1998) found that R&D spillovers constructed with randomly created trade data explain more of the productivity variation than the CH spillover measure constructed with total imports data. We show that this criticism no longer holds when capital goods imports data are used to construct the spillover variable.

To assess the importance of capital goods trade as a conduit for international R&D spillovers one needs to consider other channels that transmit knowledge across borders. It is useful to draw the distinction between embodied knowledge flows and disembodied knowledge flows. Some R&D spillovers are embodied in trade flows and foreign direct investment; other R&D spillovers are transmitted in disembodied form through the scientific literature, international conferences, international patenting, and so on. In this paper we construct an unweighted spillover variable (sum of R&D capital stocks of foreign countries) and a distance-weighted spillover variable to capture general disembodied R&D spillovers between countries. We find that the inclusion of an unweighted (or distance-weighted) spillover variable does not affect the statistical significance of the KM-weighted spillover variable, but does significantly reduce the point estimate of its coefficient.

In our study we provide estimates of the overall impact of international R&D spillovers, as well as the relative importance of R&D spillovers embodied in capital goods trade. We find that R&D investment in a G7 country yielded a rate of return of 70 per cent in the country itself, a rate of return of 37 per cent in foreign countries through channels captured by the KM-weighted spillover variable, and a rate of return of 34 per cent in foreign countries through channels captured by the unweighted spillover variable. These estimates imply that about half of the return on R&D investment in a G7 country spilled over to other OECD countries and about half of the spillovers were transmitted through channels captured by the KM-weighted spillover variable, which include but are not limited to the channel of capital goods trade (see subsection 3.3 for detailed discussion).

In comparison with recent studies on international R&D spillovers, our study has some distinctive features. On the one hand, we differ from CH and others who estimated the impact of R&D spillovers embodied in trade flows without controlling for disembodied R&D spillovers. On the other hand, we differ from Bernstein (1996), Bernstein and Yan (1997), Bernstein and Mohnen (1998), and Park (1995), who estimated the overall effect of international R&D spillovers but not the relative importance of R&D spillovers embodied in trade. Following CH, we use a simple Cobb-Douglas production function estimation approach. This approach is admittedly more restrictive than the approach adopted by Bernstein and his collaborators, which takes into account response of factor intensities to R&D spillovers.

In the rest of the paper we proceed as follows. In section 2 we discuss the regression specification. In section 3 we report empirical findings. In section 4 we conclude. Data information is contained in an appendix.

2. Framework

2.1. Regression specification

We assume that output (Y) is produced by combining labor (L), physical capital (K), and knowledge capital (S), subject to a Cobb-Douglas production function, $Y = AL^{\alpha}K^{\beta}S^{\gamma}$.[1] Defining total factor productivity (TFP) as $F = Y/L^{\alpha}K^{\beta}$, we obtain $F = AS^{\gamma}$. For an open economy, S depends on both domestic knowledge capital (S^d) and knowledge spillovers from other countries (S^f). Following CH, we assume that $S = (S^d)^{\delta}(S^f)^{\phi}$. This leads, in a panel data setting, to the following relationship:

$$\log F_{it} = c_{it} + \alpha_i^d \log S_{it}^d + \alpha_i^f \log S_{it}^f + \epsilon_{it}, \qquad (1)$$

1 This equation can be derived from innovation-driven growth models (e.g., Grossman and Helpman, 1991). See Coe and Helpman (1995) for a discussion.

where i and t are indices of country and time, respectively, c_{it} is a composite intercept term including both time- and country-specific fixed effects, α_i^d and α_i^f are elasticities, and ϵ_{it} is an error term. Equation (1) will be referred to as the level specification. An alternative is the following difference specification:

$$\Delta \log F_{it} = c_t + \alpha_i^d \Delta \log S_{it}^d + \alpha_i^f \Delta \log S_{it}^f + \mu_{it}. \qquad (2)$$

Equation (2) is the first difference of equation (1), $\Delta X_{it} = X_{it} - X_{it-1}$ for variable X. In equation (2), c_t is a time-specific constant and μ_{it} is an error term. Our study will use both level and difference regressions.[2]

2.2. Measure of R&D spillovers

As Griliches (1992) has pointed out, the major research questions in the area of R&D spillovers remain measurement questions. Authors of previous studies have dealt with the measurement of international R&D spillovers with different approaches. In studies based on two-country models, such as Bernstein (1996), Bernstein and Yan (1997), and Bernstein and Mohnen (1998), international R&D spillovers are assumed to arise from the R&D capital stock of the foreign country. In a multicountry framework, however, there is an issue of how to weight R&D capital stocks of foreign countries in aggregating them into a measure of foreign R&D spillovers. The construction of foreign R&D spillovers involves the choice of weighting scheme and the choice of weight variable.

Two alternative weighting schemes have been adopted in recent studies of R&D spillovers through trade. The weighting scheme used by CH takes the following form:

$$S_i^{f\text{-CH}} = \sum_{j \neq i} \frac{M_{ij}}{M_i} S_j^d, \qquad (3)$$

where $M_i = \sum_{j \neq i} M_{ij}$. In CH the weight variable M is total imports. Thus, Coe and Helpman measured international R&D spillovers as bilateral-imports-share-weighted sum of R&D capital stocks of trade partners.[3] Alternatively, LP proposed the following weighting scheme:

$$S_i^{f\text{-LP}} = \sum_{j \neq i} \frac{M_{ij}}{Y_j} S_j^d, \qquad (4)$$

where Y_j denotes GDP of country $j \neq i$. The LP measure assumes that a fraction M_{ij}/Y_j of country j's domestic R&D capital stock spills over to country i through

2 Both level and difference regressions have been used in the empirical literature on international R&D spillovers. For example, CH used level regressions, while Coe, Helpman, and Hoffmaister (1997) adopted difference regressions.

3 The summation in equations (3) and (4) is across foreign countries in the sample. In our study we use a sample of twenty-one OECD countries, which accounted for 96 per cent of total world's R&D expenditures in 1990.

trade.[4] LP showed that their measure significantly reduces an 'aggregation bias' in the CH measure.[5] They also found that their measure performed better empirically than the CH measure. We will use both measures to see the robustness of our qualitative results, but our quantitative assessment will be based on the LP measure, since it is found to perform better empirically than the CH measure.

The focus of our study is more on the choice of the weight variable. The weight variable reflects how R&D knowledge spills over across national borders. We will use capital goods trade and non-capital goods trade as weight variables to examine whether trade-related R&D spillovers are carried mainly by capital goods, and we will use unweighted and distance-weighted spillover variables to capture international R&D spillovers in disembodied form. We hope that these examinations will lead to better quantitative assessment of the overall impact of international R&D spillovers in the OECD, as well as the relative importance of R&D spillovers embodied in trade flows.

3. Results

Our study uses data of twenty-one OECD countries over the 1983–90 period.[6] Details of the data set are reported in the appendix. All regressions are run using ordinary least squares with White's heteroscedasticity-consistent covariance estimation method.

3.1. Testing capital goods trade against non-capital goods trade

We first examine the significance of capital goods as carriers of international R&D spillovers through trade. In table 1, regression (1.1) is a replication of CH's regression (iii) after an 'indexation bias' identified by LP is corrected for.[7] This regression specification is the preferred one of CH: the elasticity with respect to foreign R&D spillovers is assumed to be proportional to m, the share of imports in GDP. Using *indexed* R&D capital stocks, CH ran this regression and found quantitatively large R&D spillovers. LP showed, however, that applying indexed R&D capital stocks in this regression implies a misspecification of the model. They replicated the same regression by using *value* of R&D capital stocks and found that the estimated coefficient of the CH measure of foreign R&D spillovers is not significantly different from zero (regression (iv) in LP). The same result is obtained in our regression (1.1), although it is run over a shorter sample period.

The significance of foreign R&D spillovers is recovered, however, when capital goods imports are used as the weight variable instead of total imports (regression

4 Note that the 'weights' in the LP weighting scheme are exports-GDP ratios of foreign countries and do not sum to one.

5 The 'aggregation bias' refers to the problem that CH's measure of R&D spillovers are very sensitive to the level of data aggregation (e.g., merger of countries into regional groups).

6 The sample used by CH and LP covers the same twenty-one OECD countries plus Israel over the 1971–90 period. Our sample period is shorter because data on bilateral capital goods trade are available only for years after 1983.

7 The 'indexation bias' refers to a misspecification in CH's regression (iii) caused by indexation of R&D capital variables.

TABLE 1
R&D spillovers through trade: capital goods vs. non-capital goods (CH weighting scheme, pooled data 1983–90 for twenty-one OECD countries, 168 observations)

Regression number	1.1	1.2	1.3	1.4	1.5
log S^d	0.148	0.104	0.149	0.104	0.104
	(0.017)	(0.016)	(0.018)	(0.017)	(0.017)
G7 log S^d	0.158	0.171	0.158	0.171	0.171
	(0.036)	(0.033)	(0.035)	(0.033)	(0.033)
m log $S^{f-\mathrm{CH}}$(M)	0.017			−0.004	
	(0.014)			(0.016)	
m log $S^{f-\mathrm{CH}}$(KM)		0.245		0.247	0.246
		(0.032)		(0.035)	(0.033)
m log $S^{f-\mathrm{CH}}$(NKM)			0.020		−0.006
			(0.023)		(0.024)
R^2	0.709	0.771	0.699	0.772	0.772
R^2 adjusted	0.662	0.735	0.651	0.733	0.733
Root MSE	0.025	0.022	0.025	0.022	0.022

NOTES
The dependent variable is log TFP. All equations include unreported country-specific constants. S^d is domestic R&D capital stock, beginning of year; S^f(M), S^f(KM), and S^f(NKM) are foreign R&D spillovers weighted by total imports, capital goods imports, and non-capital goods imports, respectively, beginning of year; m is the ratio of M, KM, or NKM to GDP in respective cases; G7 is a dummy variable that equals 1 for the seven major countries and 0 for the other countries. Numbers in parentheses are heteroscedasticity-corrected standard errors.

1.2). Moreover, the use of capital goods imports data significantly improves the goodness of fit of the model, raising R-squared from 0.709 to 0.771. This result mitigates a criticism on the CH approach by Keller (1998), who found that R&D spillovers constructed with randomly created trade data yielded a higher R-squared (= 0.747) than that constructed with total imports data (= 0.706).

Regression (1.3) shows further that R&D spillovers weighted by non-capital goods imports are not significantly different from zero. When R&D spillovers weighted by total imports or by non-capital goods imports are included with the KM-weighted spillover variable, only the latter remains significant (regressions 1.4 and 1.5).[8]

Coe and Helpman (1995) conducted unit root tests of Levin and Lin (1992, 1993) on the pooled data and found that the variables in level regressions are non-stationary (table 2 of CH). However, their cointegration tests yielded mixed results (table 3 of CH). Our panel is too short to apply the Levin-Lin tests. We can check the robustness of our level regression results by examining results from difference regressions. Table 2 reports results from the same regressions of table 1 with first difference of variables. These results confirm that TFP is significantly correlated with R&D spillovers weighted by capital goods imports but insignificantly corre-

8 All regressions in table 1 include country-specific constants as in CH and LP. Adding time-specific effects changes little the results.

TABLE 2
R&D spillovers through trade: capital goods vs. non-capital goods (CH weighting scheme, pooled data 1984–90 for twenty-one OECD countries, 147 observations)

Regression number	2.1	2.2	2.3	2.4	2.5
$\Delta \log S^d$	0.022	0.021	0.021	0.019	0.023
	(0.025)	(0.022)	(0.026)	(0.021)	(0.022)
ΔG7 $\log S^d$	0.098	0.112	0.098	0.113	0.113
	(0.047)	(0.046)	(0.047)	(0.045)	(0.046)
$\Delta m \log S^{f-\text{CH}}(\text{M})$	0.003			−0.014	
	(0.011)			(0.015)	
$\Delta m \log S^{f-\text{CH}}(\text{KM})$		0.104		0.117	0.108
		(0.035)		(0.042)	(0.038)
$\Delta m \log S^{f-\text{CH}}(\text{NKM})$			0.002		−0.014
			(0.014)		(0.019)
R^2	0.132	0.210	0.132	0.218	0.213
R^2 adjusted	0.075	0.158	0.074	0.161	0.155
Root MSE	0.016	0.015	0.016	0.015	0.015

NOTES
The dependent variable is Δ log TFP. $\Delta X = X_t - X_{t-1}$ for variable X. All equations include unreported time-specific constants. See the notes to table 1 for variable definitions.

lated with R&D spillovers weighted by non-capital goods imports or total imports.[9]

Table 3 shows further that the result of capital goods' being major carriers of trade-related R&D spillovers is also obtained when the LP weighting scheme is used to compute foreign R&D spillovers. Regression (3.1) is a replication of LP's regression (v) in difference specification over our sample period. The LP measure of foreign R&D spillovers is statistically significant when weighted either by total imports (regression 3.1) or by capital goods imports (regression 3.2), but the use of capital goods imports significantly improves the fit of the model, raising R-squared from 0.18 to 0.25. Regression (3.4) includes both the KM-weighted spillover variable and the total-imports-weighted spillover variable, and we find that only the former is statistically significant. On the other hand, R&D spillovers weighted by non-capital goods imports are statistically insignificant (regressions 3.3 and 3.5). Thus, the results from tables 1–3 establish that R&D spillovers embodied in trade flows are mainly carried by capital goods.[10]

9 The domestic R&D variable for non-G7 countries is statistically insignificant in these regressions. This may be due to the restriction that the coefficient on the domestic R&D variable is the same for all non-G7 countries and country-specific effects enter only through the constant. We estimated a regression with country-specific coefficients on the domestic R&D variable but no constant term, and found that seventeen out of twenty-one countries have statistically significant estimated coefficients on the domestic R&D variable.

10 In applying the CH approach to the investigation of R&D spillovers from industrial countries to developing countries, Coe, Helpman, and Hoffmaister (1997) used capital goods imports as the weight variable. They did not explicitly test capital goods imports against non-capital goods imports as carriers of R&D spillovers but noted that the use of capital goods imports is 'more consistent with the theory and does a better job empirically' (140).

TABLE 3
R&D spillovers through trade: capital goods vs. non-capital goods (LP weighting scheme, pooled data 1984–90 for twenty-one OECD countries, 147 observations)

Regression number	3.1	3.2	3.3	3.4	3.5
Δ log S^d	0.010	0.015	0.016	0.024	0.023
	(0.023)	(0.021)	(0.025)	(0.021)	(0.021)
ΔG7 log S^d	0.089	0.086	0.094	0.089	0.091
	(0.045)	(0.041)	(0.047)	(0.040)	(0.040)
Δ log $S^{f-\text{LP}}$(M)	0.050			−0.054	
	(0.018)			(0.034)	
Δ log $S^{f-\text{LP}}$(KM)		0.054		0.086	0.065
		(0.013)		(0.027)	(0.016)
Δ log $S^{f-\text{LP}}$(NKM)			0.018		−0.032
			(0.017)		(0.022)
R^2	0.180	0.246	0.137	0.261	0.259
R^2 adjusted	0.126	0.196	0.081	0.207	0.205
Root MSE	0.015	0.015	0.016	0.015	0.015

NOTES
The dependent variable is Δ log TFP. $\Delta X = X_t - X_{t-1}$ for variable X. All equations include unreported time-specific constants. See the notes to table 1 for variable definitions.

3.2. Testing capital goods trade against other spillover channels

So far we have considered only R&D spillovers embodied in trade flows. But countries are technologically linked through a number of channels, not only through international trade. The knowledge of R&D can spill over through, for example, the scientific literature, overseas students, international patenting, multinational corporations, and so on. Without controlling for these other spillover channels, we cannot claim that the estimated effects of foreign R&D spillovers in tables 1–3 are due to capital goods trade. Investigation of all of these channels is beyond the scope of this paper, but we will test KM-weighted R&D spillovers against unweighted and distance-weighted international R&D spillovers.[11]

We first construct an unweighted spillover variable as the sum of R&D capital stocks of all other OECD countries in the sample. This variable captures some disembodied flows of R&D knowledge. In table 4, regression (4.2) includes both the unweighted spillover variable and the KM-weighted spillover variable (in LP measure) as regressors.[12] The result shows that the KM-weighted R&D spillover variable remains statistically significant when the unweighted foreign R&D spillover variable is controlled for. Moreover, by comparing regressions (4.1) and (4.2), we find that the point estimates of TFP elasticities with respect to both domestic R&D stocks and KM-weighted R&D spillovers are significantly reduced after unweighted foreign R&D spillovers are controlled for.

11 We also tested capital goods trade against foreign direct investment (FDI) as R&D spillover channels for a subsample of thirteen OECD countries and found that the KM-weighted spillover variable remains statistically significant when a FDI-weighted spillover variable is controlled for. Owing to the poor quality of FDI data, we do not report the results here.

12 Using the CH spillover measure generally yields the same qualitative results so we report results only from regressions using the LP spillover measure. However, see fn 17.

TABLE 4
R&D spillovers through capital goods trade: controlling for other channels (LP weighting scheme, pooled data 1983–90 for twenty-one OECD countries, 168 observations)

Regression number	4.1	4.2	4.3	4.4	4.5
log S^d	0.063	0.038	0.039	0.035	0.037
	(0.014)	(0.019)	(0.019)	(0.019)	(0.018)
G7 log S^d	0.099	0.089	0.089	0.088	0.096
	(0.027)	(0.030)	(0.030)	(0.029)	(0.030)
log $S^{f-\text{LP}}$(KM)	0.091	0.082	0.082	0.079	0.068
	(0.009)	(0.011)	(0.011)	(0.011)	(0.019)
log S^f(UW)		0.063		0.058	0.062
		(0.037)		(0.036)	(0.037)
log S^f(DIS)			0.061		
			(0.038)		
log H				0.161	0.155
				(0.081)	(0.080)
KM/GDP					0.224
					(0.263)
R^2	0.805	0.808	0.808	0.812	0.813
R^2 adjusted	0.773	0.776	0.776	0.779	0.778
Root MSE	0.020	0.020	0.020	0.020	0.020

NOTES
The dependent variable is log TFP. All equations include unreported country-specific constants. S^f (UW) and S^f (DIS) are unweighted and distance-weighted foreign R&D spillovers, respectively, H is average total school attainment, and KM/GDP is the ratio of capital goods imports to GDP. See the notes to table 1 for definitions of other variables.

As an alternative to the unweighted spillover variable, we compute a measure of foreign R&D spillovers weighted by the inverse of geographic distance.[13] Flows of disembodied knowledge may be impeded by geographic distance. In studies by Sjöholm (1996) and Eaton and Kortum (1996), for example, it was shown that geographic proximity matters for international transmission of knowledge. Regression (4.3) shows that the inclusion of the distance-weighted R&D spillover variable does not affect the statistical significance of the KM-weighted spillover variable. Again, we find that the point estimates of TFP elasticities with respect to both domestic R&D stocks and KM-weighted R&D spillovers are significantly reduced after distance-weighted R&D spillovers are controlled for.[14]

In regression (4.4) we include a human capital variable measured as average

13 $S^f(\text{DIS}) = \sum_{j \neq i}(W_{ij}/W_i)S_j^d$, where $W_i = \sum_{j \neq i} W_{ij}$, $W_{ij} = 1/\ln(D_{ij})$, and D_{ij} is the direct-line distance (in kilometres) between the major city (most likely the capital) of country i and that of country j. We thank Shang-Jin Wei for making the data available. Original data are from *Direct-Line Distances* (International Ed.) by Gary L. Fitzpatrick and Marilyn J. Modlin (1986).

14 We also ran regressions on the first difference of variables and found that the KM-weighted spillover variable remains statistically significant after the unweighted or distance-weighted spillover variable is controlled for. Difference regressions, however, yield statistically insignificant estimates of the effect of the unweighted or distance-weighted spillover variable. We base our quantitative assessment on point estimates from level regressions because they utilize information embodied in the levels data that is discarded by differencing variables.

years of total school attainment by Barro and Lee (1996). Engelbrecht (1997) argued that this variable should be included in TFP regressions. The inclusion of the human capital variable, however, changes little the estimated effects of other variables. Our results indicate, as did those of Engelbrecht (1997), that point estimates of TFP elasticities with respect to domestic R&D capital stocks become only slightly smaller after human capital is controlled for. It is clear from table 4 that the control for non-trade spillover channels is more important than the control for human capital in producing estimates of the elasticity of TFP with respect to domestic R&D capital stocks that are more in line with those found in single-country studies.[15]

The activity of capital goods trade not only transmits knowledge in embodied form, but also transmits knowledge in disembodied ways. Grossman and Helpman (1991, section 6.5) discussed ways for international trade to facilitate the exchange of ideas. As an attempt to control for any trade-related disembodied knowledge spillovers that are not captured by the unweighted spillover variable, we use the ratio of capital goods imports to GDP as an additional regressor.[16] Regression (4.5) reports the result. The KM-GDP ratio enters the regression insignificantly, but the inclusion of the KM-GDP ratio causes the point estimate on the KM-weighted spillover variable to fall from 0.079 to 0.068.[17] One important lesson from this and other regressions in table 4 is that the effect of foreign R&D spillovers embodied in trade would be overestimated if the effects of international R&D spillovers through various other spillover channels are not controlled for.

3.3. *Quantitative assessment of R&D spillovers in the OECD*

With the use of capital goods imports data and the control for the effects of disembodied R&D spillovers and human capital, we hope to estimate more precisely the overall impact of foreign R&D spillovers on OECD countries and the impact of R&D spillovers embodied in trade flows. Our quantitative assessment is based on regression (4.5), which uses the LP spillover measure.[18]

Regression (4.5) shows that a 1 per cent increase in the KM-weighted spillover variable raises TFP by 0.068 per cent, and a 1 per cent increase in the unweighted spillover variable raises TFP by 0.062 per cent. Using these two estimates, we calculate the elasticities of TFP in one country with respect to the domestic R&D

15 In studies of industrial countries, elasticities of TFP with respect to domestic R&D capital stocks are found to be in the range of 0.06 to 0.1 (Griliches 1988, 15).

16 Coe, Helpman, and Hoffmaister (1997) also used the KM-GDP ratio as a regressor. Using imports-GDP ratio or log of the KM-GDP ratio yields similar results. The regression performs the best when the KM-GDP ratio is used.

17 The inclusion of the KM-GDP ratio has a more dramatic effect on the CH measure of KM-weighted spillovers, causing its effect to be not significantly different from zero. This shows that the CH measure may capture trade-related disembodied R&D spillovers rather than R&D spillovers embodied in trade.

18 Tables 2 and 3 show that regressions on the LP measure of foreign R&D spillovers yield higher goodness of fit than those on the CH measure of foreign R&D spillovers. Moreover, regressions using the LP measure yield estimated TFP elasticities and rates of returns to R&D investment more consistent with estimates from firm- and industry-level studies (discussed in the end of this subsection).

capital stock of another country through channels captured by the KM-weighted spillover variable and the unweighted spillover variable. The results are reported in table 5.[19] In table 5 it is shown, for instance, that a 1 per cent increase in the U.S. R&D capital stock, through capital goods exports and other channels, raised the Japanese TFP by 0.084 per cent in 1990. On the other hand, a 1 per cent increase in the Japanese R&D capital stock, through capital goods exports and other channels, raised the U.S. TFP by 0.049 per cent. These estimates are larger than those obtained by CH (reported in their table 5). Moreover, the relative size of our estimated spillover elasticities seems more plausible. For example, Japan is widely believed to be one of the largest beneficiaries of U.S. technology; both Bernstein and Mohnen (1998) and Eaton and Kortum (1996) found that U.S. R&D capital accounted for about half of Japan's productivity growth. Our estimation (table 5) indicates that Japan is the second largest (next to Canada) in the elasticity of TFP with respect to the U.S. R&D stock, which contrasts sharply with CH's estimation, which ranks Japan as the second smallest in this elasticity among all OECD countries.[20] Our results also indicate that R&D spillovers from the United States to Japan are much more significant than R&D spillovers from Japan to the U.S. Table 5 shows that the elasticity of Japanese TFP with respect to U.S. R&D was about twice the elasticity of U.S. TFP with respect to Japanese R&D in 1990. By contrast, CH estimated that the elasticity of Japanese TFP with respect to U.S. R&D was only 17 per cent larger than the elasticity of U.S. TFP with respect to Japanese R&D in 1990. Our result is thus more in line with results from recent studies that show sharp asymmetry of R&D spillover effects between the United States and Japan.[21]

Table 5 also reports the average elasticity of TFP of all foreign countries with respect to the domestic R&D capital stock of a G7 country.[22] This elasticity indicates the relative importance of a country as source of R&D spillovers among the OECD. The United States is the largest source of R&D spillovers; a 1 per cent increase in the R&D stock of the United States raised TFP of other OECD countries by 0.061 per cent in 1990. We also decompose the overall spillover effect into the effect through channels captured by the KM-weighted spillover variable and the effect through channels captured by the unweighted spillover variable. Table 5 shows, for instance, that a 1 per cent increase in the U.S. R&D capital stock raised the TFP of other OECD countries by 0.026 per cent through channels captured by

19 The elasticity of country i's TFP with respect to the domestic R&D capital stock of country j is calculated according to the following formula: $\alpha_{ij} = \partial \log F_i / \partial \log S_j^d = \alpha_{km}^f \partial \log S_i^f(\text{KM}) / \partial \log S_j^d + \alpha_{uw}^f \partial \log S_i^f(\text{UW}) / \partial \log S_j^d = \alpha_{km}^f (M_{ij}/Y_j)(S_j^d / S_i^f(\text{KM})) + \alpha_{uw}^f S_j^d / S_i^f(\text{UW})$.

20 CH's rank is a result of their assumption that the elasticity of TFP with respect to foreign R&D spillovers is proportional to the share of imports in GDP. This elasticity is low for Japan mainly because Japan had a low share of imports in GDP compared with other OECD countries (except for the United States in years before 1985).

21 Bernstein and Mohnen (1998), using data over the period 1962–86, found that international R&D spillovers existed from the United States to Japan but not in the converse direction. Similar results were obtained by Branstetter (1996) using firm-level data over the period 1985–89.

22 The average elasticity of TFP of all foreign countries with respect to the domestic R&D capital stock of country j is given by $\alpha_j = \sum_{i \neq j} (Y_i / Y) \alpha_{ij}$, where Y is the sum of GDP over all $i \neq j$.

TABLE 5
Elasticities of TFP with respect to R&D capital stocks in the G7 countries, 1990

	U.S.	Japan	Germany	France	Italy	U.K.	Canada
U.S.		0.0493	0.0220	0.0106	0.0039	0.0167	0.0134
Japan	0.0844		0.0190	0.0057	0.0024	0.0088	0.0013
Germany	0.0515	0.0186		0.0157	0.0044	0.0151	0.0013
France	0.0536	0.0142	0.0271		0.0054	0.0140	0.0012
Italy	0.0416	0.0114	0.0325	0.0147		0.0120	0.0011
U.K.	0.0539	0.0163	0.0265	0.0110	0.0034		0.0015
Canada	0.0927	0.0126	0.0073	0.0044	0.0016	0.0059	
Australia	0.0678	0.0251	0.0112	0.0048	0.0022	0.0099	0.0015
Austria	0.0399	0.0140	0.0448	0.0068	0.0034	0.0077	0.0012
Belgium	0.0407	0.0119	0.0293	0.0145	0.0030	0.0112	0.0011
Denmark	0.0471	0.0144	0.0266	0.0072	0.0029	0.0142	0.0011
Finland	0.0470	0.0164	0.0238	0.0071	0.0030	0.0112	0.0013
Greece	0.0383	0.0200	0.0310	0.0097	0.0069	0.0104	0.0011
Ireland	0.0584	0.0144	0.0123	0.0062	0.0022	0.0267	0.0013
Netherlands	0.0461	0.0128	0.0282	0.0085	0.0026	0.0152	0.0013
New Zealand	0.0632	0.0242	0.0099	0.0048	0.0022	0.0118	0.0014
Norway	0.0538	0.0135	0.0206	0.0064	0.0024	0.0138	0.0012
Portugal	0.0367	0.0127	0.0228	0.0145	0.0064	0.0163	0.0010
Spain	0.0468	0.0134	0.0253	0.0146	0.0054	0.0119	0.0011
Sweden	0.0517	0.0145	0.0262	0.0075	0.0029	0.0121	0.0012
Switzerland	0.0430	0.0145	0.0377	0.0092	0.0040	0.0097	0.0011
Average elasticity							
Overall	0.0613	0.0316	0.0228	0.0101	0.0036	0.0137	0.0065
KM channels	0.0260	0.0187	0.0142	0.0045	0.0014	0.0065	0.0050
UW channels	0.0353	0.0129	0.0085	0.0056	0.0023	0.0072	0.0015

NOTES
Estimated elasticities of TFP in the row country with respect to the R&D capital stock in the column country. Based on regression (4.5) in table 4. Average elasticity refers to the elasticity of TFP of all foreign countries with respect to the R&D capital stock of the column country. Averages are calculated using PPP-based GDP weights. KM channels refer to R&D spillover channels captured by the KM-weighted spillover variable, and UM channels refer to R&D spillover channels captured by the unweighted spillover variable.

the KM-weighted spillover variable and 0.035 per cent through channels captured by the unweighted spillover variable.

Using table 5, we calculate the average rate of return on R&D investment in a G7 country that was accrued to other OECD countries. This rate of return was estimated to be 71 per cent in 1990.[23] This rate can be decomposed into two: the rate of return related to R&D spillovers transmitted through channels captured by the KM-weighted spillover variable was 37 per cent, and that related to R&D spillovers transmitted through channels captured by the unweighted spillover variable was 34 per cent.

23 The rate of return in country i on R&D investment in country j is given by $r_{ij} = \partial Y_i / \partial S_j^d = \alpha_{ij} Y_i / S_j^d$. The rate of return in all foreign countries on R&D investment in country j is $r_j = \sum_{i \neq j} r_{ij}$. The average rate of return on R&D investment in a G7 country is calculated using PPP-based GDP weights.

We can compare the spillover effects with the domestic effects of R&D investment. Regression (4.5) reports that the estimated elasticity of TFP with respect to domestic R&D capital stock is 0.037 in non-G7 countries and 0.133 in G7 countries. These two estimates imply that the own rate of return on domestic R&D investment was 40 per cent in non-G7 countries and 70 per cent in G7 countries in 1990.[24]

These estimated rates of return to R&D investment enable us to quantitatively assess the role of R&D spillovers in the OECD and the relative importance of capital goods trade as a conduit for R&D spillovers. According to our estimation for 1990, R&D investment in a G7 country yielded a rate of return of 70 per cent in the country itself, and a rate of return of 71 per cent in foreign countries in terms of R&D spillovers. This implies that about half (70/141) of the benefits from R&D investment in a G7 country were obtained by the country itself and the other half were obtained by other OECD countries.[25] In contrast, CH estimated that the own rate of return was 123 per cent in a G7 country in 1990 and the rate of return accrued to other countries was 32 per cent. Their estimates thus imply that only one-fifth (32/155) of the benefits from R&D investment in a G7 country were obtained by other OECD countries. Our study suggests that CH are likely to have underestimated the relative magnitude of international spillover effects mainly because they did not consider non-trade spillover channels in their regressions.

Our estimation also implies that about half (37/71) of international R&D spillovers in the OECD were transmitted through channels captured by the KM-weighted spillover variable. It is important to note, however, that the KM-weighted spillover variable may capture not only knowledge embodied in capital goods trade, but also knowledge contained in trade flows of R&D-intensive non-capital goods, such as software, chemicals, and pharmaceutical goods. Although non-capital goods are *on average* less R&D-intensive than capital goods, there are R&D-intensive non-capital goods that may be carriers of R&D spillovers. The effects of R&D spillovers through these R&D-intensive non-capital goods are likely to be captured by the KM-weighted spillover variable. Theoretically, a country that exports more capital goods is expected also to export more R&D-intensive non-capital goods based on its higher R&D-abundance. Empirically, we find evidence of high correlation between the share of R&D-intensive non-capital goods exports in GDP and the share of capital goods exports in GDP. For example, this correlation is 0.63 between the share of chemicals exports (SITC 5) in GDP and the share of capital goods exports in GDP in 1990 for OECD countries in our sample. By contrast,

24 The own rate of return is defined as $r_i = \partial Y_i / \partial S_i^d = \alpha_i^d Y_i / S_i^d$. In 1990 the average ratio of GDP to domestic R&D capital stock in G7 countries and non-G7 countries was 5.24 and 10.79, respectively; hence the average own rate of return on domestic R&D capital in G7 countries was $5.24 * (0.037 + 0.096) = 70$ per cent, and that in non-G7 countries was $10.79 * 0.037 = 40$ per cent.

25 Nadiri and Kim (1996, 19) reported that about 60 to 70 per cent of total return to R&D investment in a G7 country occurred domestically and 30 to 40 per cent of return occured to the trade partners in the form of R&D spillovers. They measured international R&D spillovers as in CH and did not consider spillover channels other than imports.

this correlation is only 0.35 between the share of beverages and tobacco exports (SITC 1) in GDP and the share of capital goods exports in GDP.

To distinguish the effect of R&D spillovers embodied in capital goods, we need to control for R&D spillovers embodied in R&D-intensive non-capital goods. This requires the construction of variables measuring R&D spillovers by commodity.[26] We do not attempt it because of data availability.[27] We argue, however, that the estimated effects of the KM-weighted spillover variable reflect largely the impact of R&D spillovers embodied in capital goods trade, because capital goods trade accounted for a large proportion of total trade in the OECD (see table A1) and an even larger proportion of trade in R&D-intensive goods. Thus, we conclude that trade in capital goods was a significant channel of R&D spillovers, but the amount of R&D spillovers it transmitted was less than half of total R&D spillovers in the OECD (an estimate based on the KM-weighted spillover variable). The majority of the R&D spillovers in the OECD were transmitted through other channels.

A final note on our estimated rates of return on domestic R&D capital stock. In firm- and industry-level studies, the direct rates of return on domestic R&D capital stock were found to be around 20 to 40 per cent, and the indirect rates of return through intersectoral spillovers were sometimes estimated to be over 100 per cent (Nadiri 1993, tables 1 and 2). The extremely high indirect rates of return in these single-country studies may have captured the effects of international R&D spillovers. Yet after controlling for R&D spillovers through international trade, CH still obtained rates of return on domestic R&D capital stock to be 123 per cent in G7 countries and 85 per cent in non-G7 countries, which were viewed as 'implausibly high' (Barro and Sala-i-Martin 1995, 352). By controlling for unweighted R&D spillovers and other factors, we obtain estimated rates of return on domestic R&D capital stock of 70 per cent in G7 countries and 40 per cent in non-G7 countries (based on regression 4.5).[28] Thus, the consideration of international R&D spillovers through various channels can help us to obtain better estimates of the rate of return on domestic R&D investment.

4. Conclusion

Capital goods are often assumed as carriers of international R&D spillovers in

26 In constructing the KM-weighted spillover variable, we use total R&D (relative to GDP) rather than R&D investment in capital goods (relative to output of capital goods). The variable would be more precisely measured if capital goods trade data were matched with data on R&D investment in capital goods.

27 OECD data series of R&D expenditure by industry are available for years after 1981, a period that is too short to construct R&D capital stock by industry for our sample period. Moreover, the R&D data by industry (ISIC) do not contain sufficient information to allow conversion into data by commodity (SITC).

28 Regressions that use the LP spillover measure generally yield lower estimated rates of return on domestic R&D investment than those that use the CH spillover measure. In LP the estimated rates of return can be calculated to be 76 per cent in G7 countries and 65 per cent in non-G7 countries (based on their regression (v)), which are much lower than CH's estimates but are higher than our estimates because they did not control for other spillover channels.

open-economy innovation-driven growth models. In this paper we investigated the significance of capital goods trade as a conduit for R&D spillovers and quantitatively assessed the impact of international R&D spillovers on OECD countries. We tested capital goods trade against non-capital goods trade and found it to be the major carrier of R&D spillovers embodied in trade flows. We evaluated R&D spillovers embodied in trade vis-à-vis R&D spillovers in disembodied form, and showed that the effect of R&D spillovers embodied in trade would be overestimated if other channels were not controlled for. By considering both knowledge spillovers embodied in trade flows and knowledge spillovers in disembodied form, we estimated that about half of the return on R&D investment in a G7 country spilled over to other OECD countries. We found capital goods trade to be a significant channel of R&D spillovers, although the majority of the R&D spillovers in the OECD were transmitted through other channels.

Our study is limited in several respects. First, the simple Cobb-Douglas estimation approach we adopted ignores the endogenous response of economic variables to international R&D spillovers. Second, the unweighted (or distance-weighted) spillover variable we controlled for may have captured only part of the disembodied R&D spillovers between countries; consequently, the effects of disembodied R&D spillovers are likely to have been underestimated. Third, R&D spillovers embodied in capital goods would be more precisely measured by using information on R&D investment in capital goods. These limitations should be considered when our results are interpreted.

Appendix: Data description

Data on TFP and domestic R&D capital stocks are from Coe and Helpman's (1995) appendix. TFP is defined as $Y/[K^{\beta}L^{(1-\beta)}]$, where Y, K, and L are the value-added, capital stock, and labour employment in the business sector, respectively. TFP data are indices with 1985=1. Domestic R&D capital stocks are constructed by accumulating real R&D investment, allowing for depreciation. The value of domestic R&D capital stocks in various years is calculated using CH's table A.3 (domestic R&D capital stock indices with 1985=1) and table A.7 (value of domestic R&D capital stocks in 1990). The unit of domestic R&D capital stocks is billion U.S. dollars, based on PPP's and in constant 1985 prices. For details of the construction of TFP and domestic R&D capital stocks, see CH's appendix A.

Bilateral trade data are from the OECD's *Foreign Trade by Commodities*. Data are available for years after 1983. We use imports of machinery and transport equipment (SITC 7) as a proxy for imports of capital goods, and the difference between total imports and imports of machinery and transport equipment as a proxy for imports of non-capital goods. Our sample is a panel of twenty-one OECD countries over the 1983–90 period. Table A1 reports the share of capital goods imports in total imports for the twenty-one countries averaged over the sample period. In addition, we obtain GDP data from the World Bank's World Data CD-ROM, and human capital stock data from Barro and Lee (1996). Human capital

TABLE A1
Share of capital goods imports in total imports, averaged over 1983–90

	U.S. (S.d.)	Japan	Germany	France	Italy	U.K.	Canada	OECD (S.d.)
U.S.		0.77	0.63	0.42	0.26	0.37	0.43	0.52 (0.20)
Japan	0.25 (0.03)		0.48	0.14	0.16	0.25	0.02	0.25 (0.16)
Germany	0.44 (0.04)	0.74		0.39	0.26	0.33	0.12	0.37 (0.20)
France	0.55 (0.02)	0.70	0.45		0.33	0.28	0.16	0.39 (0.19)
Italy	0.36 (0.04)	0.62	0.42	0.30		0.36	0.12	0.37 (0.16)
U.K.	0.47 (0.05)	0.75	0.54	0.36	0.36		0.16	0.37 (0.17)
Canada	0.61 (0.03)	0.76	0.56	0.34	0.26	0.26		0.55 (0.23)
Australia	0.49 (0.03)	0.71	0.53	0.39	0.39	0.36	0.25	0.51 (0.18)
Austria	0.49 (0.04)	0.80	0.41	0.41	0.25	0.38	0.24	0.42 (0.18)
Belgium	0.29 (0.04)	0.80	0.39	0.25	0.28	0.19	0.09	0.29 (0.19)
Denmark	0.48 (0.09)	0.80	0.39	0.31	0.38	0.30	0.21	0.35 (0.20)
Finland	0.55 (0.05)	0.81	0.57	0.44	0.43	0.32	0.19	0.44 (0.21)
Greece	0.26 (0.04)	0.87	0.36	0.24	0.33	0.31	0.13	0.36 (0.19)
Ireland	0.62 (0.02)	0.84	0.46	0.30	0.35	0.20	0.41	0.37 (0.19)
Netherlands	0.36 (0.03)	0.74	0.32	0.28	0.32	0.28	0.31	0.34 (0.17)
New Zealand	0.47 (0.09)	0.66	0.48	0.37	0.50	0.41	0.25	0.48 (0.23)
Norway	0.65 (0.05)	0.80	0.51	0.43	0.41	0.30	0.13	0.39 (0.21)
Portugal	0.21 (0.05)	0.85	0.46	0.43	0.52	0.37	0.05	0.43 (0.21)
Spain	0.35 (0.10)	0.68	0.55	0.42	0.50	0.31	0.14	0.46 (0.18)
Sweden	0.57 (0.06)	0.78	0.53	0.42	0.41	0.27	0.33	0.41 (0.19)
Switzerland	0.43 (0.04)	0.72	0.38	0.23	0.24	0.22	0.24	0.35 (0.18)

NOTES
Capital goods imports as a share of total imports in the row country from the column country. The first column shows the mean (standard deviation over time) of the share in the row country with respect to the United States over the period 1983–90. The last column shows the mean (standard deviation over countries) of the share in the row country with respect to all other OECD countries in 1990.

stock is measured as average years of total school attainment in the population over age twenty-five. The human capital stock of 1980 is used for 1983–85 and that of 1985 is used for 1986–90.

References

Barro, R., and J. Lee (1996) 'International measures of schooling years and schooling quality,' *American Economic Review* 86, 218–23

Barro, R., and X. Sala-i-Martin (1995) *Economic Growth* (New York: McGraw-Hill)

Bernstein, J.I. (1996) 'R&D spillovers between U.S. and Canadian industries,' *Canadian Journal of Economics*, Special Issue, pt 2, S463–7

Bernstein, J.I., and P. Mohnen (1998) 'International R&D spillovers between U.S. and Japanese R&D intensive sectors,' *Journal of International Economics* 44, 315–38

Bernstein, J.I., and X. Yan (1997) 'International R&D spillovers between Canadian and Japanese industries,' *Canadian Journal of Economics* 30, 276–94

Branstetter, L. (1996) 'Are knowledge spillovers international or intranational in scope? Microeconomic evidence from the U.S. and Japan,' NBER Working Paper No. 5800

Coe, D.T., and E. Helpman (1995) 'International R&D spillovers,' *European Economic Review* 39, 859–87

Coe, D.T., E. Helpman, and A.W. Hoffmaister (1997) 'North-South R&D spillovers,' *Economic Journal* 107, 134–49

Eaton, J., and S. Kortum (1996) 'Trade in ideas: Patenting and productivity in the OECD,' *Journal of International Economics* 40, 251–78

Engelbrecht, H. (1997) 'International R&D spillovers, human capital and productivity in OECD economies: an empirical investigation,' *European Economic Review* 41, 1479–88

Griliches, Z. (1988) 'Productivity puzzles and R&D: another nonexplanation,' *Journal of Economic Perspectives* 2, 9–21

— (1992) 'The search for R&D spillovers,' *Scandinavian Journal of Economics* 94, S29–S47

Grossman, G.M., and E. Helpman (1991) *Innovation and Growth in the Global Economy* (Cambridge, MA: MIT Press)

Keller, W. (1998) 'Are international R&D spillovers trade-related? Analyzing spillovers among randomly matched trade partners,' *European Economic Review* 42, 1469–81

Levin, A., and C.F. Lin (1992) 'Unit root tests in panel data: asymptotic and finite-sample properties,' Discussion Paper No. 92-23, University of California, San Diego

— (1993) 'Unit root tests in panel data: new results,' Discussion Paper No. 93-56, University of California, San Diego

Lichtenberg, F., and B. van Pottelsberghe de la Potterie (1998) 'International R&D spillovers: a comment,' *European Economic Review* 42, 1483–91

Nadiri, M.I. (1993) 'Innovations and technological spillovers,' NBER Working Paper No. 4423

Nadiri, M.I., and S. Kim (1996) 'International R&D spillovers, trade and productivity in major OECD countries,' NBER Working Paper No. 5801

Park, W.G. (1995) 'International R&D spillovers and OECD economic growth,' *Economic Inquiry* 33, 571–91

Rivera-Batiz, L.A., and P.M. Romer (1991) 'Economic integration and endogenous growth,' *Quarterly Journal of Economics* 106, 531–55

Sjöholm, F. (1996) 'International transfer of knowledge: the role of international trade and geographic proximity,' *Weltwirtschaftliches Archiv* 132, 97–115