International Trade and Economic Growth:
A Methodology for Estimating Cross-Border R&D Spillovers

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1 Introduction

The Bureau of Economic Analysis (BEA) initiated in 2004 a National Science Foundation (NSF) funded project to produce an official BEA/NSF R&D Satellite Account (R&DSA).[1] The R&DSA differs from the National Income and Product Accounts (NIPAs) in that, unlike the NIPAs, the R&DSA capitalizes R&D and allows for the estimation of R&D's contribution to economic growth. Although BEA has decided not to include domestic or international spillovers in the R&DSA (or in the core accounts), research identifying the nature and extent of spillovers has been conducted in connection with this project. This paper presents a trade-based methodology for estimating country-level cross-border R&D spillovers and the econometric results from the model.[2]

The research indicates that U.S. outward spillovers to 20 OECD countries and inward spillovers from the G-6 countries to the U.S were each approximately $700 billion in 1990.[3] Further research could investigate additional channels of transmission, refine estimation techniques, and improve the conceptual basis for placing the estimates in perspective in relation to other relevant economic aggregates.

The globalization of national economies and technological connectivity of international businesses has resulted in a world in which a country's economic growth is dependent upon domestic, as well as foreign, R&D investment. Thus, when R&D investment occurs in one country, and a portion of the subsequent benefits of that investment accrue to other countries, those benefits are termed *cross-border R&D spillovers*. As will be shown, a nonperforming country can benefit from spillovers through the increased effectiveness of its existing factors of production. Spillovers can thereby lead to an increase in that country's level of productivity and lower production costs.

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[1] Satellite accounts provide a framework linked to the central account which enables attention to be focused on a certain field or aspect of economic and social life in the context of national accounts; examples are satellite accounts for travel and tourism and household production.

[2] The impact of cross-border R&D spillovers at the firm level could be to hasten exit by less productive firms or to raise the productivity of all firms. This paper focuses on country-level effects because of the potential difficulty of generalizing from firm-level to country-level effects.

[3] The sample set of G-6 countries was used to measure inward spillovers to the U.S. because these countries (plus the U.S.) represented approximately 92 percent of OECD R&D expenditures in 1990.

The structure of the paper follows. Section Two provides background on the nature of R&D spillovers. Section Three highlights the recent cross-border R&D spillover literature, including a discussion of the channels of transmission and the Grossman and Helpman model, which is this paper's aggregate approach to estimating spillovers. Section Four discusses an evolution of the Grossman and Helpman model. Section Five represents the heart of this paper because it provides a methodology for quantifying R&D spillovers. Section Six concludes and provides important suggestions for future research.

2 Identifying Embodied and Disembodied R&D Spillovers

Generalizing R&D spillovers as one type of input or capital flow is typical of most research. The goal of this section is to elaborate on some of the important conceptual issues that often go unmentioned with this simple inputs approach. Specifically, this section examines the theoretical arguments of the roles embodied and disembodied R&D spillovers play in determining economic growth.

The non-rival and non-excludable characteristics of R&D capital are well-documented. Non-rival means nonperformers of the R&D technology can acquire it at virtually zero marginal cost. Non-excludability refers to the fact that performers cannot completely prevent nonperformers from benefiting from the technology. The fact that R&D is non-excludable is what leads to technological benefits being transferred to nonperformers, or transfers of R&D spillovers. Such "imperfect appropriation" by R&D performers implies that there is always some form of domestic and/or international spillover (externality) associated with R&D capital investment (Bernstein, 1994). Moreover, these spillovers occur regardless of whether the domestic R&D investment leads to performers' product or processes innovations.[4]

Griliches (1979) first identified two sources of spillovers that are generated by R&D investment: rent spillovers and knowledge spillovers. Rent spillovers are a type of pecuniary externality which, unlike knowledge spillovers, transmits through market transactions in the form of changes in productivity, cost reductions, or quality

[4]This is an area of research that requires more exploration. While numerous studies exist which highlight the differences between product and process innovations, Ornaghi (2006) is a rare addition that relates these differences to spillovers.

improvements (Kim, 2005). These changes are embodied in traded goods through domestic and foreign R&D activities. In a comprehensive survey of cross-border R&D spillovers, Cincera and van Pottelsberghe de la Potterie (2001) state:

> Rent spillovers arise because the prices of intermediate inputs are not fully adjusted for quality improvements resulting from R&D investments in other countries…They originate exclusively from economic transactions…Knowledge spillovers arise because of the imperfect appropriability of the knowledge associated with spillovers…They occur when ideas (knowledge) are 'borrowed' by a research team in country *j* from a research team in country *i*…Knowledge spillovers are not directly embodied in economic transactions…Since these knowledge spillover channels are often associated with an economic transaction, the extent to which they also reflect some rent spillovers is not so clear cut.

This statement underscores the overlap between rent and knowledge spillovers within the same transaction.[5] Disentangling measured values of rent and knowledge spillovers within a modeling framework is outside the scope of this paper. Instead, I measure the impact of two related concepts: *embodied* and *disembodied* R&D spillovers.

Though similar conceptually, knowledge and disembodied spillovers are distinct with regard to ease of measurement. Disembodied R&D spillovers are easier to capture since, throughout the literature, the definition does not allow for spillover transmissions to occur through the purchase of goods; whereas knowledge spillovers can be acquired by nonperformers either through the purchase or non-purchase of goods from performers.[6] With regard to embodied R&D spillovers and rent spillovers, they more closely relate to one another since they both represent how new technology physically diffuses only through the purchase of goods.

What are the implications of these concepts for the channels of transmission and the estimation of those channels within a modeling framework? Although disembodied R&D spillovers do not, in principle, result from the purchase of goods, increased amounts of trade and foreign direct investment (FDI) between nations will nonetheless increase their international diffusion. For example, if the United States and Japan increase bilateral trade or FDI, contact between American and Japanese importers, exporters, and

[5] Researchers should also be concerned that quantitatively separating rent from knowledge spillovers may result in significant multicollinearity bias. See Cincera and van Pottelsberghe de la Potterie (2001) for graphical illustration of knowledge and rent spillover flows.

[6] For example, disembodied R&D spillovers are transmitted through international conferences or scientific journals.

scientists will invariably increase (Keller, 2004).[7] As contacts between highly skilled persons with advanced technological knowledge increases, knowledge transmissions and the occurrence of disembodied R&D spillovers also tend to increase. Moreover, local goods may not embody the same technological characteristics as imports. Therefore, increased commercial relations can serve as a catalyst for insights by local researchers through the use and inspection of new goods (Grossman and Helpman, 1991). Second, Keller (1998) and Xu and Wang (1999) concluded that the impact of R&D spillovers embodied in trade would be overestimated if disembodied channels were not controlled for.

3 Literature Review

Research exploring linkages between economic growth, domestic R&D capital, and foreign R&D capital has abundantly grown over the past 15 years, largely as a result of improved modeling techniques and the increasing availability of micro-level data sources. In their survey paper, Cincera and van Pottelsberghe de la Potterie (2001) documented research that has provided strong evidence that R&D implemented in any country contributes to global productivity growth. They also emphasize that research on the measurement and effectiveness of spillover flows through non-trade channels of transmission should be further developed.

3.1 Channels of Transmission

In the literature, the cross-border channels of transmission of embodied R&D spillovers are international trade and foreign direct investment/multinational companies (MNCs), while the disembodied channel is represented by the transmission of knowledge and ideas (e.g. international conferences, scientific journals, and patents). Much of the literature on international trade as a transmission channel focuses on very specific aspects of trade and productivity relationships, such as measuring the volume of trade (Coe and Helpman, 1995), capital vs. non-capital goods trade (Xu and Wang, 1999), the

[7]Keller also recognizes that disembodied R&D spillovers are difficult to estimate with a high degree of certainty because they reflect the acquisition of technology that is not connected to any particular form. However, he concluded that these types of spillovers may be a stronger form of technology diffusion than spillovers occurring through intermediate goods trade.

importance of relative country sizes (Eaton and Kortum, 1999) and nations' geographic distance relative to one another (Harhoff, 2000 and Branstetter, 2000). The importance of imports as a conduit for R&D spillovers has received positive attention recently. Blalock and Veloso (2004) provided a relatively rare micro-level study which assesses imports as integral for international technology transfer. On the other hand, learning-by-exporting does not appear to be an important spillover channel (Keller, 2004).

With regard to the FDI channel, the literature emphasizes three transmission sub-channels: 1) domestic firms learning efficiency-enhancing production techniques from foreign MNCs ('demonstration effect'), 2) competition from MNCs resulting in improved productivity in domestic firms ('competition effect'), and 3) the movements of highly skilled staff from MNCs to domestic firms (Gorg and Strobl, 2001). Although research has been underway since the mid-1960s, the results are very mixed as to which of these sub-channels are conduits for positive spillovers. In their meta-analysis, Gorg and Strobl emphasized that in order to gauge the significance of these sub-channels, it is very important to utilize lengthy time-series FDI data as opposed to cross-sectional data. Finally, the literature provides evidence that firm-specific innovations transfer across borders through MNC parent and subsidiary technology sharing (Branstetter, 2000).

Patents are widely viewed as a robust source of information for studying innovation and technical change (Hall, Jaffe, and Trajtenberg, 2001). Attempts to capture the spillovers associated with international knowledge flows have relied specifically on patent citation or licensing data (Al-Azzawi, 2004). In a study designed to measure R&D spillovers from trade and patents, Xu and Chiang (2005) found that the rate of foreign patenting is determined by growth of world R&D stocks, intensity of capital goods imports from innovating countries, and by the capability of domestic countries to adopt foreign technology.

3.2 Modeling Cross-Border R&D Spillovers

The utilization of complex models to measure the domestic impact of foreign R&D investment has grown, though there is no widely accepted approach due to the aforementioned difficulties involved with the estimation. Keller (2004) stated that the majority of research attempting to measure cross-border spillovers employ regression

analysis.[8] These studies are predominately at the aggregate (industry- or country-) level of analysis and many are based on Grossman and Helpman's innovation-led model.[9] The next section introduces this model's fundamental theoretical properties.

3.2.1 The Grossman and Helpman Model and R&D Spillovers

Traditional growth theory highlights the incentives for capital accumulation while technological progress (innovation) is viewed as an exogenous process. Grossman and Helpman (1991, hereafter GH) were important contributors to the development of a new growth theory which is based on endogenous innovation.[10] As in Romer (1990) and Aghion and Howitt (1992), the GH model adopted the Schumpterian position, whereby successful ongoing innovation results in some amount of market power which creates opportunities to profit and reinvest in R&D activities.[11] Fundamentally, GH ground their theoretical foundations within an oligopolistic setting rather than the traditionally competitive and establish the stylized fact that R&D incorporates, in every case, some of the spillovers which are inherent in the knowledge generation process. They treat knowledge capital as an input into R&D, therefore at any point, fewer additional factors of production are needed to produce new types of product.

Their model elucidates endogenous innovation as a means for improving the understanding of the relationship between trade and long run growth. In their simplified version of the model, they incorporate trade, knowledge accumulation, and endogenous growth to emphasize that when final goods are traded on international markets, international trade can have a positive or negative impact on a country's domestic innovation process.[12] Increased trade can have a positive effect on R&D activities

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[8]He cautions that researchers should be aware that these models are only able to partially capture spillovers and that these types of models typically cannot account for endogeneity problems (i.e. what determines R&D).

[9]Historically, comparable cross-country data (such as patent flows, intermediate inputs, and investment goods) at the firm level have been difficult to assemble. Although, there is a growing availability of micro-level data, which has resulted in more studies increasingly relying on traditionally microeconomic cost and production functions, such as the flexible translog production function, to measure the impact of foreign R&D spillovers. See the conclusion for more on the translog.

[10]See the appendix for an elaboration of the GH model.

[11]See Romer (2001, Chapter 3) for a theoretical overview of the development of new growth theory in macroeconomics.

[12]This also depends on whether that country is an importer or exporter of goods. The model also predicts that foreign R&D leads to the creation of new intermediate inputs for nonperformers.

because it leads to increased flows of technological information from foreign countries, which leads to increased productivity, ceteris paribus. By making technological progress a function of world output of an intermediate good, the domestic nonperformers who import the intermediate good would automatically acquire the R&D spillover benefits from foreign performers.[13] Increased trade can have a negative effect on R&D activities, according to GH, if:

> In the trade situation the world economy has a relatively greater abundance of unskilled labor than the human capital-rich country…As a result the integrated economy undertakes more of the activity that uses unskilled labor intensively. Thus the scale of industrial research activities may shrink in the human capital-rich country despite the productivity gains that result from any international spillovers of knowledge.[14]

4 Evolution of the Grossman and Helpman Model

Next, four studies are presented, which test the GH assumption that imports into a domestic economy embody technological knowledge. These studies include contributions from Coe and Helpman (1995), Keller (1998), Lichtenberg and van Pottelsberghe de la Potterie (1998), and Xu and Wang (1999). Useful references are contained in Appendix 2, which is an essential equations list with an accompanying description of notation, and Appendix 3, which is a comparative table of the estimation results from the equations discussed throughout this section.

4.1 Coe and Helpman (1995)

Coe and Helpman (hereafter CH) derived a simplified version of the GH-model to test for cross-border R&D spillovers among OECD countries and were succeeded by numerous economists who modified the model. It is important to note that the model was tested using developed country samples. This is so because domestic R&D data in many relatively poor or developing nations is difficult to obtain and because the majority of global R&D is conducted by developed countries.

For their study of 21 OECD countries plus Israel from 1971-1990, CH used a relatively simple single equation regression model. They related total factor productivity

[13]Oftentimes, nonperformers have to invest funds into the acquisition of spillover benefits. Therefore, this model does not capture the full impact of international R&D spillovers. Grossman and Helpman's later life-cycle models account for the cost factor of nonperformer imitation.

[14]Conversely, if the imported items are human capital-rich, then increased flows lead to lower costs of domestic innovation because of decreased derived demand for human capital.

to both foreign and domestic R&D and estimated a quantitatively large and positive effect from their import-weighted foreign R&D variable. Their simplest equation took the form:

$$\log F_{it} = \alpha_i + \alpha^d \log S_{it}^d + \alpha^f \log S_{it}^{f-CH} + \varepsilon_{it} , \qquad (1)$$

where F_{it} is total factor productivity (TFP), i = 1,…., 22 is a country index, $t = 1,\ldots, 20$ is a time index (1971-1990), and α_i is a country-specific constant.[15] Domestic R&D capital stocks S_{it}^d are constructed based on the empirical literature which takes the aggregate of domestic R&D expenditures as a proxy for a stock of knowledge. Foreign R&D capital stocks S_{it}^{f-CH} are constructed identically as domestic stocks but are import-weighted, which constrains the impact of foreign R&D to be identical for all countries.[16] They are denoted as

$$S_{it}^{f-CH} = \sum_{j \neq i} \frac{m_{ijt}}{m_{it}} S_{jt}^d , \qquad (2)$$

where m_{ijt} is the import flow of goods and services of country i from j, m_{it} is total imports of country i from its 21 trade partners, and S_{jt}^d is the domestic R&D capital stock of trade partners. This equation indicates that the more country i imports from countries with a relatively high R&D expenditure, the more R&D spillovers country i will receive, ceteris paribus.

[15]This model is known as a *fixed effect model* because the intercept differs across countries, but each country's intercept is time invariant. Varying country intercepts allows for the recognition of each country's special characteristics.

[16]Domestic and foreign R&D capital stocks are calculated based on the perpetual inventory method, which does have an allowance for depreciation. See Coe and Helpman's (1995) Appendix A for the methodology and Tables A.3 and A.5 for the final domestic and foreign capital stocks, respectively. It is important to note that the R&D capital stock data, which is used by other authors including Xu and Wang, may be misestimated. The R&D deprecation rate is set by Coe and Helpman at 5 percent; the R&D depreciation rate used in Fraumeni and Okubo (2004) varies from 11 to 20 percent. In addition, Coe and Helpman do not assume that there is either a gestation or application lag, e.g., they assume that all R&D is completed in the year it is initiated and that benefits begin to accrue to performers and non-performers in that same year. Fraumeni and Okubo employed a one-year lag to capture both effects and examine as part of the BEA/NSF project whether this is the appropriate lag structure and whether the benefit stream from R&D might be lumpy. Spillovers should be assumed to occur with lags if there is a gestation or an application lag. The lag and benefit stream might differ for cross-border spillovers from that for domestic spillovers or for performers of R&D.

Their second equation allows the impact of domestic R&D to differ between the G-7 and non-G-7 economies. This is a measurement of the separate impact of G-7 domestic R&D capital stocks from the non-G-7 countries in the sample.[17] CH interact the domestic R&D capital stock with a dummy variable valued at 1 for the G-7:

$$\log F_{it} = \alpha_i + \alpha^d \log S_{it}^d + \alpha^{G7} G7 \log S_{it}^d + \alpha^f \log S_{it}^{f-CH} + \varepsilon_{it} \quad . \tag{3}$$

Their final equation drops the constraint in (1) and (3) with respect to S_{it}^{f-CH} and interacts an import share effect with the foreign R&D capital stock. CH note that this technique allows for country-specific, time-varying elasticities on foreign R&D. The equation is noted as

$$\log F_{it} = \alpha_i + \alpha^d \log S_{it}^d + \alpha^{G7} G7 \log S_{it}^d + \alpha^f \left(\frac{m_{it}}{y_{it}} \right) \log S_{it}^{f-CH} + \varepsilon_{it} \quad , \tag{4}$$

where $\frac{m_{it}}{y_{it}}$ is a country's ratio of total imports to gross domestic product (GDP), also known as the import share or import intensity.

CH established that foreign R&D has a potentially larger effect on domestic total factor productivity the greater the domestic economy is open to international trade and that domestic R&D has a significantly higher impact on TFP the larger the country's GDP (for example, the G-7 countries have much larger estimated elasticities of TFP regarding their domestic R&D). Letting $m = \frac{m_{it}}{y_{it}}$, CH estimated $\alpha^f m$ as 0.294—the elasticity with respect to the share of imports in GDP in equation (4), which indicate quantitatively large R&D spillovers, and an R^2 of 0.651.

4.2 Keller (1998)

Significant modifications of the CH framework were made by other economists, with particular regard to the S_{it}^f equation. Keller (1998) argued that CH's import shares are not paramount in the construction of the S_{it}^f variable. In his construction of foreign

[17]One could expect G-7 R&D investment to have a larger impact on total factor productivity since the G-7 constitutes the overwhelming majority of global R&D investment. This exception is confirmed in Table 3 of CH. For non-G-7 countries, the estimated elasticity of productivity was 0.089, while the G-7 elasticity was 0.134.

R&D capital stocks S_{it}^{f}, he utilized randomly created import shares and the estimation yielded similarly high coefficients as in the CH study. Keller utilized a methodology he denotes as *counterfactual estimation*, in which his models consist of Monte-Carlo experiments where the CH regressions are repeated with foreign knowledge stock variables.[18] These variables were then computed based on counterfactual (simulated) trade patterns.[19] In comparison to CH's estimation results, Keller established that his simulated foreign knowledge stock variable better explained part of the variation in TFP levels. Specifically, Keller's elasticity of TFP with respect to the import share-weighted foreign R&D capital stock $\alpha^{f} m$ was 0.329 and his R^2 was 0.747 for equation (4). In comparison to CH's $\alpha^{f} m$ of 0.294 and R^2 of 0.651, Keller's results indicated that CH's import shares are not essential determinants of increased productivity.[20] Keller's variables also performed better than CH's in equations (1) and (3).

Additionally, Keller computed cross-border R&D spillovers given that S_{it}^{f-CH} was the unweighted simple sum of foreign countries' R&D stocks, denoted as

$$S_{it}^{f-CH} \Rightarrow \overline{S}_{it}^{f} = \sum_{h \neq i} S_{ht}^{d} . \tag{5}$$

Obviously, with the absence of import share-weighted domestic R&D stocks, trade patterns do not affect the S_{it}^{f} variable. Keller found that the simple sum of foreign R&D stocks α^{f} yielded significantly higher R&D spillover estimations; Keller's α^{f} was 0.335 compared to CH's 0.294 in equation (4). Also, utilizing S_{it}^{f} as a simple sum variable resulted in higher $R^2 s$ than those from all three of CH's equations. Keller's conclusion confirms that international trade plays a role in embodied technological diffusion, but measuring the magnitude of R&D spillover's relation to international trade patterns should take place in a model where trade-unrelated (or disembodied) technology

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[18]Monte Carlo experiments are essentially sampling experiments used to study the statistical properties of various methods of estimating population parameters. It is a useful technique for Keller's repeated sampling experiment.

[19]The complete methodology is explained in Keller (1998) on page 1476.

[20]In a response to Keller (1998), Coe and Hoffmaister (1999) demonstrated that Keller's random weights were basically simple averages with a random error. Coe and Hoffmaister further showed that, through the use of alternative random weights used to define the foreign R&D capital stock variable, the spillover estimates were, as expected, nonexistent.

diffusion can occur simultaneously. Keller's conclusion alludes to the importance of the distinction between *embodied* and *disembodied* spillovers, which was discussed earlier.

4.3 Lichtenberg and van Pottelsberghe de la Potterie (1998)

Other economists have made further strides regarding the impact to productivity from R&D spillovers. Lichtenberg and van Pottelsberghe de la Potterie (hereafter LP) advanced the literature by finding that the CH weighting scheme is subject to an aggregation bias. They contend that, given CH's S_{it}^{f-CH} equation, if nations merge, there would always be an increase in the stock of CH's foreign R&D capital stock (see equation (2)). LP's alternative measurement is

$$S_{it}^{f-LP} = \sum_{j \neq i} \frac{m_{ijt}}{y_{jt}} S_j^d \quad , \tag{6}$$

where y_{jt} is country *j's* GDP. This measurement considers the percentage of imports from country *j* to country *i* with respect to the GDP of country *j* (the scale factor). LP finds this measure particularly useful because it eliminates the aggregation bias while reflecting the direction and intensity of R&D spillovers.[21]

Additionally, LP cited an indexation bias and attempted to improve CH's statistical methodology. LP noted that due to the presence of fixed country effects, CH's S_{it}^{f-CH} variable would be imprecise because CH measure S_{it}^{f-CH} as index numbers (1985=1, or $S_{i,1985}^{f}=1$) and multiply them by the import share $\frac{m_{it}}{y_{it}}$.[22] LP contend that this term cannot be added into the country-specific constants because it is not time invariant.[23] By taking equation (4) and expressing the explanatory variables as levels instead of indices, the estimated coefficient of the foreign R&D capital stock becomes 0.004 (S.E. 0.004) as opposed to CH's estimate of 0.294 (S.E. 0.041). By comparison, the decreased (and statistically insignificant) explanatory power of LP's coefficient

[21]LP prove an example of the aggregation bias in their paper on page 1486. They demonstrate the sensitivity of US and Japanese foreign R&D capital stock, given a merger of the 11 European Community countries included in their sample.

[22]Fixed country effects are time-invariant parameters representing the unique characteristics of countries that affect TFP independently of R&D stocks.

[23]LP elaborate on this issue on pages 1486-1487.

suggests an indexation bias in CH's model, in which the impact of the foreign R&D capital stock on TFP, as measured by CH, is misspecified.

To correct for this misspecification, LP created a reformulated version of equation (4) denoted as

$$\log F_{it} = \alpha_i + \alpha^d \log S_{it}^d + \alpha^{G7} G7 \log S_{it}^d + \alpha^f \left(\frac{m_{it}}{y_{it}} \right) \log S_{it}^{f-LP} + \alpha^m \left(\frac{m_{it}}{y_{it}} \right) + \varepsilon_{it} \qquad (7)$$

in which the import share $\frac{m_{it}}{y_{it}}$ is added as an additional regressor which avoids establishing restrictions on the productivity elasticities. In LP's estimation of equation (7), utilizing equation (6) as the scale factor, their finding of –2.768 for the elasticity α^m indicated that the import share $\frac{m_{it}}{y_{it}}$ has a negative relationship with TFP, which shows that the import share matters less than the distribution of the originating countries. Additionally, they found a relatively higher (than CH's) foreign R&D elasticity α^f of 0.310 and an R^2 of 0.700.

The conclusion here is that both the CH and LP equations demonstrate that the more open an economy is to trade, the more it will benefit from foreign R&D. LP's construction of α^f led to an additional finding that foreign R&D's impact on domestic TFP will increase with increased imports from R&D intensive countries. LP developed significant improvements in correcting for the CH model's aggregation and indexation biases.[24] Still, future economists would find additional techniques to advance the model.

[24]Since the computed t-values indicate the error correction terms are significantly different than zero and stationary, the equations are considered to be cointegrated. Edmonds (2001) enumerated concerns beyond the scope of this paper regarding CH's, Keller's, and LP's results being sensitive to the estimation methodology. Given the relevance of heterogeneous slope coefficient specification, Edmonds suggested that some attention be given to alternative group mean estimation results. Edmond's conclusion was that models derived from the CH approach are subject to misspecification, unable to reject a spurious regression null, or yield coefficient signs which are sensitive to whether one utilizes pooled or group mean estimations. Keller's models passed Edmond's panel cointegration tests and his group mean estimation approaches appeared relatively robust. However, Edmond suggested that CH and LP reevaluate their panel cointegration approaches and consider utilizing the more robust pooled FM or panel ARDL methods. These methods would serve to decrease the bias in estimating their long-run parameters.

4.4 Xu and Wang (1999)

Xu and Wang (hereafter XW) found that CH estimated the impact of spillovers embodied in trade flows and did not control for disembodied trade flows. As a result, their study focused on the relationship between TFP, capital goods trade, and disembodied transmission variables within the framework of the CH model.[25] Sveikauskus (2005) considers XW's contribution particularly insightful because of the range of potential channels they assess as well as the specific information regarding rates of return.

XW's model includes a measure of the domestic R&D capital stock, the R&D transmitted through capital goods, and the disembodied flow of information. Based on equation (4), they undertook a comprehensive quantitative assessment of CH's and LP's approaches separately, while specifying capital goods imports, instead of total imports, as the weight variable for both approaches. XW contend there are two reasons to separate capital from non-capital goods in these models. First, capital goods contain higher elements of technology and, therefore, are the primary goods that convey R&D spillovers within trade flows. Second, XW demonstrate that the portion of capital goods among total imports is highly volatile.

They conclude that trade in capital goods is a significant source of R&D spillovers in OECD countries. Using a levels approach similar to LP, XW's capital-goods-weighted foreign R&D variable S_{it}^{f-CH} increases the goodness of fit of equation (4). The R^2 in CH's model was 0.651, while the R^2 in the XW approach was 0.771 (although CH's elasticity coefficient $\alpha^f m$ was 0.294 compared to XW's 0.245). Additionally, XW's variable performed better than Keller's R^2 of 0.747. When XW weighted their foreign R&D variable by non-capital goods imports, domestic R&D spillovers were not different from zero.

These results must be mitigated by the reality that international linkages are established outside the channels of trade in goods, as Keller suggests. Therefore, XW controlled for non-trade related spillover channels, specifically by adding unweighted,

[25] XW's sample consisted of 21 OECD countries over the 1983-1990 period, which is similar to CH's sample set with the exception of Israel. The period is shorter than CH's because bilateral capital goods data were only available after 1983.

distance-weighted, human capital regressors into equation (3).[26] They also added an import intensity variable $\frac{m_{it}}{y_{it}}$ as a regressor to control for the presence of any disembodied knowledge spillovers which were not captured by their unweighted variable. When XW implemented LP's weighting scheme and levels approach in equation (3), while separately controlling for these variables, they found in all cases that the elasticity coefficient α^f is highly reduced, yet remained statistically significant. The goodness of fit, however, remained generally the same for all the tests.

The coefficient α^f declined the most—to 0.068—when controlling for the unweighted, human capital, and import intensity variables in the following equation:

$$\log F_{it} = \alpha_i + \alpha^d \log S_{it}^d + \alpha^{G7} G7 \log S_{it}^d + \alpha^f \log S_{it}^{f-LP}(KM) + \alpha^{uw} \log S_{it}^f(UW) + \alpha^h \log H_{it} + \alpha^m \left(\frac{m_{it}}{y_{it}}\right) + \varepsilon_{it}, \tag{8}$$

where $\log S_{it}^{f-LP}(KM)$ is the capital good imports-weighted foreign R&D stock variable, $\log S_{it}^f(UW)$ is the unweighted foreign R&D stock variable, and $\log H_{it}$ is the human capital variable. The coefficients on the unweighted, human capital, and import intensity variables in equation (8) all were insignificant.[27]

It can be concluded that XW offer a more comprehensive look into the factors impacting productivity with respect to foreign R&D spillovers than their predecessors because, as equation (8) shows, they control for the disembodied variables specifically through the testing of capital goods trade against non-trade spillover channels. Based on these tests, XW's layered analysis points to the fact that the significance of foreign R&D spillovers embodied in trade can be overestimated if one does not control for disembodied and non-trade-related spillovers.

[26]The unweighted variable equals the sum of R&D capital stocks of all other OECD countries in the sample, similar to the approach taken by Keller in equation (5). The human capital variable equals average years of school attainment measured by Barro and Lee (1996). The distance-weighted variable is a measurement of foreign R&D spillovers weighted by the inverse of geographic distance. XW further specify the calculations for the distance variable on page 1266.
[27]The import intensity variable may be picking up the impact of other unspecified variables, such as distance, language, similarity in tastes, and costs of trade.

5 Estimating Cross-Border Spillovers

This approach is a very generalized treatment of cross-border R&D spillovers. A possible methodology for constructing "net outward spillovers" utilizes XW's elasticity figures. XW calculated the estimated elasticities of TFP in the 21 sample countries with respect to the stock in the G7 countries.[28] The following formula represents α_{ij}, the elasticity of country *i's* TFP with respect to the domestic R&D capital stock of country *j* (the elasticities are presented in tables 1 and 2):[29]

$$\alpha_{ij} = \frac{\partial \log F_i}{\partial \log S_j^d} \Rightarrow \left[\frac{\alpha_{km}^f \partial \log S_i^f(KM)}{\partial \log S_j^d}\right] + \left[\frac{\alpha_{uw}^f \partial \log S_i^f(UW)}{\partial \log S_j^d}\right]$$
$$\Rightarrow \alpha_{km}^f \left[\left(\frac{M_{ij}}{Y_j}\right)\left(\frac{S_j^d}{S_i^f(KM)}\right)\right] + \left[\frac{\alpha_{uw}^f S_j^d}{S_i^f(UW)}\right] \tag{9}$$

In order to estimate cross-border spillovers, XW's rate of return equation was algebraically reorganized to:

$$r_{ij} = \frac{\partial Y_i}{\partial S_j^d} = \alpha_{ij} \frac{Y_i}{S_j^d} \quad \Rightarrow \quad r_{ij} S_j^d = \alpha_{ij} Y_i \tag{10}$$

where r_{ij} equals the rate of return in country *i* on R&D investment in country *j* and Y_i is GDP in country *i*.[30] Given this formulation, $r_{ij} S_j^d$ represents the nominal dollar value of cross-border spillovers to country *i* from country *j*.

[28]The results are found in table 5 on page 1269.
[29]These elasticities are overall elasticities computed using equation (9), including both the imported capital goods channel effect and the unweighted trade R&D stocks effect. The average over all countries elasticity corresponding to Table 1 is the sum of the imported capital goods channel effect estimate of .0260 and the unweighted trade intensity channel effect .0353. A split between these two effects is not available in XW on a country-by-country basis.
[30]This rate of return formula was also used in Coe and Helpman. In this equation, the elasticity of country *i* productivity with respect to country *j* R&D capital stock is multiplied by the GDP of country *i* (Y_i) to convert the results from a percent to a level change in GDP. A percent change in productivity transmits one-to-one to a percent change in GDP.

Outward Spillovers

Table 1
OECD Country Elasticities of TFP with respect to R&D Capital Stocks in the U.S., 1990

Japan	0.0844	Austria	0.0399	New Zealand	0.0632
Germany	0.0515	Belgium	0.0407	Norway	0.0538
France	0.0536	Denmark	0.0471	Portugal	0.0367
Italy	0.0416	Finland	0.0470	Spain	0.0468
U.K.	0.0539	Greece	0.0383	Sweden	0.0517
Canada	0.0927	Iceland	0.0584	Switzerland	0.0430
Australia	0.0678	Netherlands	0.0461		

Source: Xu and Wang (1999). Based on equation (8) and (9).

With the use of the data in Table 1, calculating cross-border outward spillovers is a two-step process. First, multipy each country's 1990 elasticity by its 1990 GDP to ascertain the cross-border spillovers it received from the U.S. For example, by multiplying Japan's TFP elasticity (0.0844) by its GDP (1990=$3,039.7 billion), one calculates $256.5 billion as Japan's cross-border spillovers.[31] Second, sum all the cross-border outward spillovers, which total $686.0 billion and effectively represent the total nominal dollar value of spillovers to other countries from the US. As a percentage of U.S. GDP (1990 = $5,803.1 billion), outward spillovers are 11.82%.

Inward Spillovers

Table 2
U.S. Elasticities of TFP with respect to R&D Capital Stocks in Selected OECD Countries, 1990

	Japan	Germany	France	Italy	U.K.	Canada
U.S.	0.0493	0.022	0.0106	0.0039	0.0167	0.0134

Source: Xu and Wang (1999). Based on equation (8) and (9).

With the use of Table 2, calculating cross-border inward spillovers was also a two-step process. First, sum all of the U.S. elasticities, which amount to 0.1159. Second,

[31]All GDP figures, except those for the U.S., were obtained from the OECD Statistical Database. U.S. GDP figures are drawn from BEA NIPA tables. There is a less than 1 percent difference between the BEA and OECD U.S. GDP figures.

multiply that figure by U.S. GDP (1990=$5,803.1 billion) to get $672.6 billion, which represents the total nominal dollar value of spillovers to the U.S. from other countries. As a percentage of 1990 U.S. GDP, inward spillovers are 11.59%.[32] To calculate net outward spillovers, subtract inward spillovers from outward spillovers to ascertain a nominal dollar value of $13.4 billion.

As noted earlier, BEA has decided not to include international spillovers in the R&DSA. R&D spillovers are a non-market phenomena and therefore do not fit into the national accounting framework, as noted by the standard-setting 1993 System of National Accounts. Spillovers do not meet the criteria for inclusion in production accounts, which require that transactions occur between consenting parties. Further research is needed to determine spillovers' relationship to other economic aggregates.

This research underscores the existence of measurement difficulties that are associated with country-level spillover analyses. Moreover, if additional countries or channels of transmission were included in the current model, there is a reasonable likelihood that the estimations of spillover flows to and from the United States would increase, ceteris paribus.

6 Conclusion and Suggestions for Future Research

This study evaluated four methodologies used to estimate the impact of cross-border R&D spillovers on economic growth. By comparative analysis, XW was selected as a framework for calculating net outward spillovers due to its straight-forward emphasis on examining capital goods trade-based embodied and disembodied channels of R&D transmission at the country-level of analysis.

This paper did not account for the response of factor intensities to cross-border R&D spillovers. Therefore, additional research could better determine the advantages of measuring spillovers within a formal cost or production function framework. For example, the flexibility of the translog production function allows for the full modeling of substitution or complementarity between factors of production. This flexibility is important because the assumption of constancy of factors of production is restrictive, particularly in large panel data sets, which are often used to analyze spillovers. Also, the

[32]The summation of elasticities is always equal to the inward spillover percentage of U.S. GDP for a given year.

translog permits a non-unitary elasticity of substitution between inputs. Given that technology is an important input, this permissibility allows for a more realistic and factor-based depiction of spillovers' impact on the production structure of the economy.[33]

Future research could also include capturing additional channels of R&D transmissions—such as FDI and international knowledge flows (specifically patents)—which would allow for the estimation of several spillover channels within a unified model.[34] Also, researchers could better understand the impact of R&D spillovers by extending the time frame to incorporate more current data and by expanding the country sample set in the model.[35] Incorporating additional years and countries would provide a more accurate and robust assessment of spillovers' potential affects on economic growth. Finally, the task of relating estimates of R&D spillovers to major economic aggregates remains a considerable challenge.

[33]The translog specification is primarily suitable for analysis of micro-level productivity performance. While it can be useful in deriving results with macro-level data, as shown in Nadiri and Kim (1996), it would be difficult to allow for the inclusion of multiple channels of transmission because the model would require the estimation of an extreme number of parameters. This would result in potentially excessive data demands and require parametric restrictions that would have to be tightly imposed in order to avoid identification issues.

[34]Patent data could be acquired from NBER's US Patent Data Citations File, which contains information on almost 3 million U.S. patents granted between January 1963 and December 1999, as well as all citations made to these patents between 1975 and 1999 (over 16 million).

[35]The expansion could include a selection of benchmarked US trading and FDI partners, including China and India.

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Appendix 1: Additional Information on the Grossman and Helpman Model

The following basic theoretical foundations of the GH model is offered to provide readers with additional background to better understand the advantages, as well as the limitations, of the model in measuring international R&D spillovers. Given its extensive treatment throughout the literature, a comprehensive discussion has been avoided. To reference the original treatment of the GH model, see Grossman and Helpman, 1991, respectively; for a detailed summary, see Helpman, 1992.

Grossman and Helpman Model

Assume a basic Cobb-Douglas function with constant returns to scale in which output is proportional to the aggregate employment of intermediate inputs:

$$Y = AL^{\beta}K^{1-\beta}n^{\alpha}, \qquad \alpha, \beta > 0; \alpha + \beta < 1 \qquad \text{(1a)}$$

where Y represents output, *A* is a constant, *K* is the physical capital stock, *L* is the employment of labor, and variable *n* represents a range of employable intermediate goods in a country. As R&D investment occurs in the country, available inputs expand as an increasing function of domestic R&D investment. Therefore, changes in TFP will depend on cumulative domestic R&D. If TFP is defined as the usual

$$f = \frac{Y}{L^{\beta}K^{1-\beta}}, \qquad \text{(1b)}$$

then replacing *Y* and taking logs, one derives

$$f = \frac{AL^{\beta}K^{1-\beta}n^{\alpha}}{L^{\beta}K^{1-\beta}} \Rightarrow \log f = \log A + \alpha \log n. \qquad \text{(1c)}$$

Equation (1c) shows that the range of horizontally differentiated goods *n* is positively related to TFP and that changes in domestic R&D will explain the large majority of TFP variation. Finally, given the assumption that all intermediate goods are traded internationally and are identical in all countries, a single country's R&D stock becomes accessible to the world. Therefore, domestic R&D's productivity impact resembles the impact of foreign R&D which could be embodied in traded goods. In order to account for these theoretical assertions of the GH model, Coe and Helpman estimate country-

level variations in TFP that are explained by (nontraded) domestic as well as (trade-embodied) foreign R&D stocks.

Appendix 2: Essential Equations[36]

<u>Coe and Helpman</u>

$$\log F_{it} = \alpha_i + \alpha^d \log S_{it}^d + \alpha^{G7} G7 \log S_{it}^d + \alpha^f \left(\frac{m_{it}}{y_{it}} \right) \log S_{it}^{f-CH} + \varepsilon_{it} \qquad (4)$$

where $$S_{it}^{f-CH} = \sum_{j \neq i} \frac{m_{ijt}}{m_{it}} S_{jt}^d \qquad (2)$$

<u>Lichtenberg and van Pottelsberghe de la Potterie</u>

$$\log F_{it} = \alpha_i + \alpha^d \log S_{it}^d + \alpha^{G7} G7 \log S_{it}^d + \alpha^f \left(\frac{m_{it}}{y_{it}} \right) \log S_{it}^{f-LP} + \alpha^m \left(\frac{m_{it}}{y_{it}} \right) + \varepsilon_{it} \qquad (7)$$

where $$S_{it}^{f-LP} = \sum_{j \neq i} \frac{m_{ijt}}{y_{jt}} S_{jt}^d \qquad (6)$$

<u>Xu and Wang</u>

$$\log F_{it} = \alpha_i + \alpha^d \log S_{it}^d + \alpha^{G7} G7 \log S_{it}^d + \alpha^f \log S_{it}^{f-LP}(KM) + \alpha^{uw} \log S_{it}^f(UW) + \alpha^h \log H_{it} + \alpha^m \left(\frac{m_{it}}{y_{it}} \right) + \varepsilon_{it}, \qquad (8)$$

$\log F_{it}$ = TFP, *i* is a country index, *t* is a time index

α_i is a country-specific constant, time invariant

m_{ijt} is the import flow of goods and services of country *i* from *j*

m_{it} is total imports of country *i* from its 21 trade partners,

y_{jt} is country *j's* GDP

$\log H_{it}$ is country *i*'s human capital

S_{it}^d is domestic R&D capital (the aggregation of domestic R&D expenditures)

S_{jt}^d is the domestic R&D stock of trade partners

S_{it}^{f-CH} is the import-weighted foreign R&D stock

S_{it}^{f-LP} is the import intensity-weighted foreign R&D stock

$\log S_{it}^{f-LP}(KM)$ is the capital goods import intensity-weighted foreign R&D stock

$\log S_{it}^{f}(UW)$ is the unweighted foreign R&D stock

[36] Numbers in parentheses correspond with paper equations.

Appendix 3: Estimation Results

Following Lichtenberg and van Pottelsberghe de la Potterie (1998), the table below is a comparison of estimation results from the equations discussed in this paper. Equations in bold correspond with the essential equations from Appendix 2. Standard errors are in parentheses.

General Description	Author	Equation #	Estimation Findings						
			α^d	α^{G7}	α^f	α^{uw}	α^h	α^m	R^2
Explanatory variables as indices, 1985=1	**CH**	**4**	**0.078** **(0.008)**	**0.156** **(0.015)**	**0.294** **(0.041)**	**--**	**--**	**--**	**0.651**
	LP	--	0.078 (0.008)	0.145 (0.016)	0.276 (0.044)	--	--	--	0.634
Capital Goods Imports, 1985=1	XW	--	0.104 (0.016)	0.171 (0.033)	0.245 (0.032)	--	--	--	0.771
Random Import Shares	Keller	--	0.035 (0.002)	0.097 (0.002)	0.125 (0.003)	--	--	--	0.728
	Keller	--	0.048 (0.001)	0.159 (0.001)	0.329 (0.005)	--	--	--	0.747
Simple Sum	Keller	--	0.032 (0.010)	0.095 (0.016)	0.129 0.014)	--	--	--	0.729
	Keller	--	0.047 (0.008)	0.159 (0.014)	0.335 (0.030)	--	--	--	0.748
Explanatory Variables as Levels	LP	--	0.103 (0.008)	0.144 (0.017)	0.004 (0.004)	--	--	--	0.600
	LP	--	0.059 (0.008)	0.086 (0.017)	0.109 (0.012)	--	--	--	0.665
	LP	--	0.082 (0.008)	0.145 (0.016)	0.249 (0.043)	--	--	-3.014 (0.529)	0.628
	LP	**7**	**0.082** **(0.007)**	**0.112** **(0.015)**	**0.310** **(0.026)**	**--**	**--**	**-2.768** **(0.239)**	**0.700**
Capital Goods Imports, Levels	XW	--	0.063 (0.014)	0.099 (0.027)	0.091 (0.009)	--	--	--	0.805
	XW	**8**	**0.037** **(0.018)**	**0.096** **(0.030)**	**0.068** **(0.019)**	**0.062** **(0.037)**	**0.155** **(0.080)**	**0.224** **(0.263)**	**0.813**