INTERNATIONAL MACROECONOMIC R&D SPILLOVERS

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This paper fulfils four functions. First, it presents a self-contained survey of research on international R&D spillovers. Second, a number of new results are presented and briefly discussed. Third, the policy implications of the various empirical findings are examined, and finally, this paper outlines a number of relevant issues in econometric methodology. It is argued that two fundamental econometric problems combine to inherently *limit* the relevance of this R&D spillovers literature. However, despite these limitations, the macroeconomic approach to R&D spillovers provides additional information on a number of interesting issues in macroeconomics and international trade. In particular, the literature so far indicates that the returns to R&D capital are distributed in rough accordance with factor proportions theory and that more recent models of "semi-endogenous" growth are better supported than are the first wave of endogenous innovation models.

1. INTRODUCTION

The collection of theoretical models associated with recent research on long run economic growth can be roughly categorised according to whether they emphasise human capital accumulation and incidental learning-by-doing or the role of technical progress. Human capital-oriented models try to account for cross-sectional variations in per capita national income by making the transitional effects of changes in a broader notion of a "capital stock" take longer. These models preserve the qualitative predictions of the traditional Solow (1956) model, but alter its quantitative predictions. In "augmented Solow" models, such as that of Mankiw, Romer and Weil (1992), the initial conditions of an economy, including natural and

* This paper was written while I was an Honours student at the University of Queensland. I would like to thank Elhanan Helpman and Charles Jones for providing access to some of the data used in my research on R&D spillovers. Helpful comments and feedback were received from two anonymous referees, my Honours' thesis supervisor – Philip M. Bodman, James Benjamin and participants in seminars at the Australian National University and the University of Queensland. The views expressed in this paper are those of the author and not necessarily those of the Reserve Bank of Australia. All errors and omissions are my own.

human resource endowments, remain important determinants of an economy's growth performance for much longer than is implied by the physical capital-oriented Solow model.[1] While these augmented Solow models have some success in explaining cross-sectional variations in *levels* of per capita income, they retain an exogenous notion of technical progress and have less success at explaining cross-sectional variations in growth rates.

Rather than assuming exogenous technical progress, endogenous innovation models are explicitly designed to show how an economy's per capita income can grow in the long run, even if diminishing returns to capital accumulation are allowed. The primary difference between Romer (1990) and older versions of endogenous growth theory, such as Arrow (1962), is the way in which concepts like "knowledge" and "ideas" are treated.[2] In Arrow's approach, knowledge accrues as an incidental Marshallian external economy of scale.[3] Knowledge is a pure public good, generated by the joint actions of an industry, not appropriable by any one member of the industry, and compatible with perfectly competitive microeconomic foundations. In Romer (1990) and Grossman and Helpman (1991) however, patents and copyrights and other technical and legal barriers exist to give a degree of monopoly power to the providers of new inventions. The possibility of monopoly power gives firms in these models an incentive to invest in R&D and creates an imperfectly competitive structure in the model industry.

Although endogenous innovation models are widely considered to give a richer account of R&D and its importance for the industrial structure of an economy, the macroeconomic implications of such models have not been the focus of much empirical attention.[4] The comparative neglect of the innovation models can be attributed to three factors. First, the most complete R&D theories are highly complex and many of the concepts invoked by such theories cannot be readily measured. Second, the reduced forms of the more complex models are observationally equivalent. These problems with the more detailed models have meant that empirical research has focused on simpler versions of these models. The third factor is that these simpler models of innovation have an unattractive feature for they predict that growth *rates* are an increasing function in population *levels*. This

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[1] Since human capital may not be as readily mobile as other forms of capital, due, say, to strategic complementarities, augmented Solow models can also explain persistent rates of return differentials between developing and industrialised economies. Lucas (1990), for example, argues that such differentials cannot be convincingly explained without recourse to some broader notion of capital.

[2] Solow (1997: 1-41) discusses in detail the relationship between Arrow (1962) and newer theories of endogenous innovation.

[3] That is, as a benefit external to individual firms but internal to the economy.

[4] As the reader is doubtless aware, human capital approaches, with their "conditional convergence" implications, have however, been the subject of an enormous empirical literature. See Barro and Sala-i-Martin (1995).

prediction is overwhelmingly rejected by post War data (India has not grown noticeably faster than Singapore) and has contributed to the relative neglect of the whole class of endogenous innovation models.[5]

Despite this neglect, a small empirical literature on one important aspect of *open economy* endogenous innovation models has become established. Following Coe and Helpman (1995), this literature examines the extent to which the benefits of investment in R&D spill across geographic boundaries. This research – which may be thought of as a subset of previous research on the international transfer of technology – is of considerable importance in considering the policy implications of endogenous innovation approaches.[6] In particular, when considering the effects of once-off policy changes like trade liberalisation or further economic integration, open economy endogenous innovation models only predict convergence in growth *rates* and only if knowledge spills over perfectly between the countries under consideration (Feenstra 1996). Except under restrictive conditions, these open economy models do not predict convergence in levels of national income. If two countries have different initial conditions and their growth rates do not converge, then their levels of national income can diverge. If knowledge does not spillover, then the process of open economy endogenous growth does not yield the egalitarian steady-state outcomes of the Solow or augmented Solow models. Consequently, research on international R&D spillovers provides information on both the time series and cross section implications of economic growth.

The remainder of this paper is structured in a simple manner. Section 2 surveys the basic approach to international R&D spillovers developed by Coe and Helpman (1995), and discusses a number of extensions and criticisms of the original findings. Section 3 examines in more detail the policy implications of the R&D spillovers literature, with particular emphasis on the new results of Edmond (1998), while section 4 makes some cautionary remarks concerning some relevant issues in econometric methodology. Section 5 offers some concluding remarks about the usefulness of the macroeconomic approach to R&D spillovers and its importance to empirical research on economic growth. In brief, it is argued that a combination

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5 Kremer (1993) has ingeniously shown how to test this "scale effect" over the very long run, and finds support for its presence in pre Second World War data. Post War evidence on the scale effect is presented in Jones (1995a,b). In the light of this research, a number of "semi-endogenous" growth models that do not have scale effect predictions have been developed. See Young (1998) and Jones (1997).

6 Recent research on R&D spillovers from industrialised to developing countries, such as Coe, Helpman and Hoffmaister (1997), is closely related to earlier work by Vernon (1966), Findlay (1978) and Krugman (1979) on the international transfer and diffusion of technology. The "contagion" theory of technology transfer developed by Findlay (1978) is probably the most similar to the arguments that Coe and Helpman (1995) adopted to explain their modelling strategy. In this paper, I will primarily restrict my survey to more recent – though much narrower – writings on R&D spillovers between industrialised countries.

of fundamental econometric problems and the macroeconomic nature of the approach inherently limit the confidence with which conclusions drawn from research into R&D spillovers can be held.

2. INTERNATIONAL MACROECONOMIC R&D SPILLOVERS

2.1 Estimating R&D Spillovers

In a recent study of 21 OECD countries and Israel over 1971-1990, Coe and Helpman (1995) use a simple "expanding variety" model of innovation developed by Grossman and Helpman (1991) to show that an economy's output can be expressed as a function of its *effective* accumulated R&D expenditures.[7] By combining this implication with neoclassical factor pricing assumptions, Coe and Helpman are able to provide estimates of a country's own return to its R&D capital and the world return to that capital. The relative difference between these "private" and "social" returns gives an indication of the magnitudes of international R&D spillovers. The key to this estimation procedure is the separation of a country's effective R&D capital into its *domestic* R&D and its *foreign* R&D capital.

An individual country's R&D capital stock is found by accumulating real expenditures according to the perpetual inventory method:

$$S_{it}^{d} = (1-\delta)S_{it-1}^{d} + R_{it-1}, \quad \text{given } S_{i0}^{d} \tag{1}$$

where S_{it}^{d} is the domestic stock of R&D, R_{it-1} is last period's new domestic R&D expenditure and δ is an assumed depreciation rate, say 0.05.[8] This process also requires estimates of an initial value for the domestic R&D stock, S_{i0}^{d}. For a given country, stocks of foreign R&D capital, S_{it}^{f}, are found by weighting each other country's domestic stock by bilateral import shares. That is, $S_{it}^{f} = \Sigma_l \, (m_{ilt} \, / \, M_{it}) \, S_{lt}^{d}$, where (m_{ilt} / M_{it}) is the share of country l in country i's total imports, M_{it}. Coe and Helpman use *indices* (with 1985 = 1) of these two stock measures and a total factor productivity measure, F, defined in Solow residual fashion. The basic regression estimated is:

$$\ln F_{it} = \alpha_i^0 + \alpha_i^d \ln S_{it}^d + \alpha_i^f \ln S_{it}^f + u_{it}, \tag{2}$$

where $u_{it} \sim N(0, \sigma_{ui}^2)$. In this equation, the a^0 are country specific constants, while a^d and a^f are the elasticities of TFP with respect to the domestic and foreign R&D capital stocks respectively.

The formulation in equation (2) accounts for the bilateral *composition* of imports. Consider two countries that are identical except in terms of the relative

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7 Detailed accounts of the relevant theory are given in Grossman and Helpman (1991) and Barro and Sala-i-Martin (1995). The specific justification for estimating productivity in terms of accumulated R&D expenditures ("R&D capital") is given in Bayoumi, Coe and Helpman (1996) and Coe et al (1997).

8 As is customary, Coe and Helpman (1995) experiment with a variety of depreciation rates for sensitivity purposes, but 0.05 is their preferred parameter.

importance of their respective trade partners. Equation (2) suggests a country that has relatively more bilateral trade with high productivity partners should itself exhibit higher productivity than an otherwise identical country that trades with low productivity partners (Keller 1997). However, this does not consider the way in which an outright *volume* of imports might create a larger channel through which knowledge can spillover. As it stands, equation (2) suggests that two countries A and B with identical import shares with respect to a third country C, will gain an equivalent bilateral knowledge spillover from C, even if country A's total volume of trade (as a proportion of national income) is significantly higher than B's. Coe and Helpman's (1995: 863) alternative and preferred specification includes both these effects. They use each country's overall import share, (M_{it}/Y_{it}), as a measure of *aggregate* openness and estimate, where $\nu_{it} \sim N(0,\sigma_{\nu i}^2)$:

$$\ln F_{it} = \alpha_i^0 + \alpha_i^d \ln S_{it}^d + \alpha_i^{G7} G7 \ln S_{it}^d + \alpha_i^f (M_{it}/Y_{it}) \ln S_{it}^f + \nu_{it}. \quad (3)$$

This preferred specification includes an interactive dummy for the G7 countries on the domestic capital stock variable. Regressions (2) and (3) essentially correspond to two different, but related, hypotheses concerning trade and growth (Keller 1997). The first, which can be labeled the "import composition" effect, is specific to models of endogenous innovation and trade. The second, the "import share effect, is more general – and can be found throughout the literature on trade and growth. The critiques of the Coe and Helpman study discussed below can be broadly categorised in terms of which effect is more closely scrutinised.

As a practical matter, Coe and Helpman *pool* their panel data over the cross section and time series. Estimation of (3) can be used to provide two sets of elasticities. First, the regression coefficients provide direct estimates of the responsiveness of a country's productivity to both its domestic and its foreign stocks of R&D capital. Second, estimates of the bilateral *cross* elasticity of one country's productivity with respect to another country's domestic R&D capital can be provided. As discussed above, a country's output can be written as a function of its effective R&D capital stock (accumulated R&D expenditures). If this function is of the generalised Cobb-Douglas aggregate production function form, then the cross elasticities, α_{il}, are just the exponents on the variable S_l^d, where l is an alternative index for the country set:

$$Y_i = A(S_i^d)^{\alpha_i^d} (S_l^d)^{\alpha_{il}},\ A \in (0,\infty). \quad (4)$$

This is where the neoclassical factor pricing assumption is required. If the returns to a capital stock are defined in terms of a scarcity index with returns equal to marginal productivity, then the elements in a rate of returns matrix $[\rho_{il}]$ can be found from the first partial derivatives of the components of the output vector:

$$\rho_{il} = \frac{\partial Y_i}{\partial S_l^d} = \alpha_{il}\left(\frac{Y_i}{S_l^d}\right). \quad (5)$$

When $i = l$, equation (5) computes the own return to a country's R&D capital stock. By summing up the total returns to a country's R&D capital (the "world return") and comparing this to the own return, a measure of the "international R&D spillovers" involved can be found. This practice can be followed for every year in the sample period, but Coe and Helpman focus only on the year 1990.

2.2 Descriptive Statistics

Coe and Helpman's calculations show that both TFP and R&D capital stocks have tended to increase over time. With the exception of New Zealand, whose 1990 TFP index was only 90% of its 1971 index, all of the countries in their sample experienced rising levels of TFP over the 1971-1990 period. Japan and Norway experienced the largest increases in TFP, with 1990 indices of 170 and 150% of the 1971 indices respectively. Most other countries exhibited some fluctuations around a generally increasing trend. All countries experienced rising domestic R&D capital stocks over the period with the increases being dramatic in the less wealthy OECD economies, such as Greece (19-fold!) and to a slightly more sober extent, Spain (7-fold). Foreign R&D capital stocks were more stable, with the United States experiencing the fastest increase (its 1990 stock was 3.4 times its 1971

TABLE 1

SUMMARY STATISTICS FROM COE AND HELPMAN

	F_{1990}/F_{1971}	S_{1990}/S_{1971} (domestic)	S_{1990}/S_{1971} (foreign)	*M/Y* (percent)	
				1971	1990
USA	1.1	2.0	3.4	5.5	11.2
JPN	1.7	4.2	1.7	9.6	9.3
DEU	1.2	2.6	1.6	19.1	26.1
FRA	1.4	1.8	1.7	15.3	22.8
ITA	1.4	2.8	1.4	15.6	19.6
GBR	1.3	1.3	1.8	21.4	27.7
CAN	1.1	2.7	1.9	20.0	25.5
AUS	1.1	4.9	2.0	14.7	18.6
AUT	1.2	3.6	2.3	30.8	38.9
BEL	1.4	2.3	1.5	43.9	88.2
DEN	1.2	2.3	1.9	30.9	31.1
FIN	1.4	4.5	2.2	26.8	25.4
GRC	1.2	18.7	1.7	17.0	32.0
IRE	1.3	3.7	2.3	42.1	56.1
ISL	1.3	7.3	1.6	50.0	52.0
NLD	1.2	1.5	1.9	45.1	53.9
NZL	0.9	2.1	2.3	25.5	22.6
NOR	1.5	4.0	2.0	45.3	37.7
PRT	1.3	2.0	1.4	33.6	44.9
ESP	1.2	7.0	1.2	14.7	21.4
SWE	1.1	3.5	1.9	22.8	31.6
SWZ	1.1	1.3	1.9	39.1	38.3

Source: Coe and Helpman (1995: 864).

stock). This indicates a general rise in the accumulated stock of knowledge outside the US but within the OECD and Israel and may be loosely interpreted as further evidence in favour of technological catch-up and convergence within the OECD economies (see Table 1).

Figures 1 and 2 chart, respectively, the domestic and foreign R&D capital stock series for a selected group of countries. Notice that the domestic R&D stock of Canada is negligible compared to that of the United States, but that Canada's foreign R&D stock is the highest of all the countries (here and in the full sample). This is because the foreign R&D stock is computed by weighting Canada's partners' domestic stocks by bilateral trade shares. The United States has the largest domestic stock by far and dominates Canada's bilateral trade, so *ceteris paribus*, Canada has the largest foreign R&D stock. The same phenomenon holds true for Australia and its bilateral trade with the United States and Japan.

2.3 A Survey of Recent Findings

Coe and Helpman (1995: 872-5) use the method outlined in section 2.1 to calculate implied rates of return to R&D capital. Their calculations indicate that the own rate of return to investment in R&D averaged 123% for the G7 as a group and averaged 85% for the remaining 15 countries in their sample. The worldwide rate of return to R&D investment by the G7 was derived as 155%. Approximately a quarter of the benefit from R&D investment by the G7 is a positive spillover to the rest of the world.[9]

The original Coe and Helpman study has been extended in a number of ways. Coe, Helpman and Hoffmaister (1997) examine the absolute size and relative importance of technology spillovers from the industrialised "North" to a developing "South". Amongst their findings is the result that developing countries have, in aggregate, larger elasticities of TFP with respect to Japan's R&D stock than to the United State's. Bayoumi, Coe and Helpman (1996) use the results from Coe and Helpman (1995) and Coe et al (1997) in econometric simulations of the role of international R&D spillovers within the world trading system. Four major *qualitative* findings were obtained from these simulations. First, sustained increases in the levels of R&D expenditures are required (over, say, a ten year period) for the R&D capital stock to generate significant effects on the growth rate of national income.

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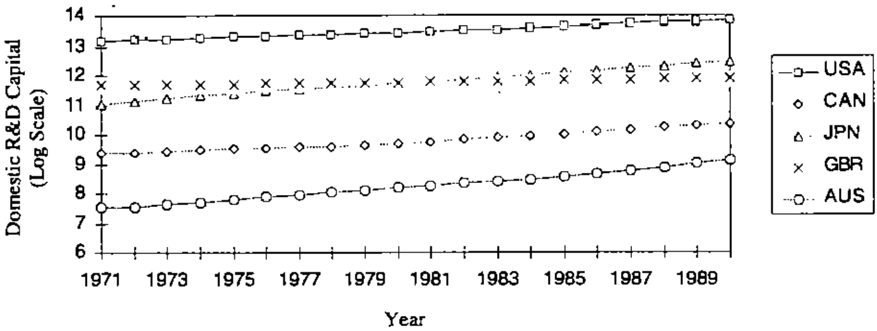
9 As discussed by Griliches (1979) and Verspagen (1997), spillovers that result from trade in goods are not pure externalities. Pure knowledge externalities (due, for example, to international conferences or specialist publications) are not compensated in the market place in the way that the "rent" externalities arising from the productivity benefits of trade in goods are. In a competitive environment, the productivity benefits from trade should be incorporated into the price of the traded goods. Pure knowledge externalities arise when a firm that creates knowledge cannot completely appropriate the benefits of higher productivity in the form of higher prices. This distinction is primarily a microeconomic concern, since there is an enormous degree of difficulty in distinguishing the two concepts at the macroeconomic level.

FIGURE 1

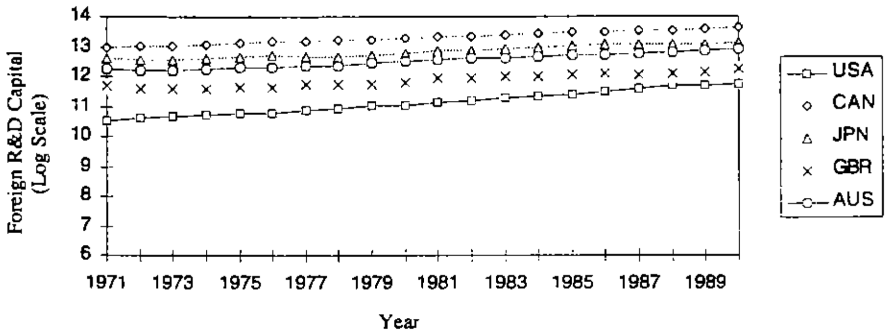
DOMESTIC R&D CAPITAL STOCKS, SELECTED COUNTRIES



Source: nominal domestic currency R&D expenditures from the OECD's *Analytical Database on Business Expenditure on Research and Development* were deflated and converted to 1985 USD at PPP exchange rates. Real expenditures were then accumulated using the perpetual inventory method, a depreciation rate of 0.05 and the estimated initial values reported by Coe and Helpman (1995). See Edmond (1998: 5-6) for further details.

FIGURE 2

FOREIGN R&D CAPITAL STOCKS, SELECTED COUNTRIES



Source: trade-weighted domestic R&D capital stocks as discussed in section 2.1. The trade weights used are taken from the International Monetary Fund's *Direction of Trade Statistics*.

Second, spillovers are largest between European countries, between Canada and the US, and between developing and industrialised countries. Third, countries that increase R&D expenditures face falling terms of trade, and finally, relative openness can lead to productivity improvements (1996: 26).

Recently, Engelbrecht (1997) has used data on human capital to augment Coe and Helpman's basic approach. He shows that the inclusion of both a human capital variable and a generic "catch-up" variable to account for innovation outside of the R&D sector produces lower estimates of the elasticity of productivity with respect to both domestic and foreign R&D capital stocks.[10] Engelbrecht also finds that the qualitative difference between the G7 and the other OECD countries in the sample is higher when human capital is considered and that the role of human capital in knowledge diffusion is distinct from that of trade. These results suggest that R&D spillovers are quantitatively less important than Coe and Helpman's results originally implied.

Lichtenberg and van Pottelsberghe de la Potterie (1996, LP hereafter) correct an apparent flaw in Coe and Helpman's theoretical model and present data on the relative importance of foreign direct investment (FDI) as an alternate source of international R&D spillovers. LP's paper is primarily concerned with *import share* effects. They argue that the specification used by Coe and Helpman in equations (2) and (3) suffers from an aggregation bias due to the method used to calculate the foreign R&D capital stock. LP show that this procedure potentially overstates a country's foreign R&D capital stock[11] and propose an alternative calculation of the foreign capital R&D stock. Finally, LP (1996: 5-7) also show that Coe and Helpman's transformation of the foreign capital R&D stocks into indices leads to mis-specification of Coe and Helpman's preferred estimation equation. The index number transformation produces a time-varying term that cannot be incorporated into the country-specific constants. To show this, rewrite equation (3) as:

$$\ln F_{it} = \alpha_i^0 + \alpha_i^d \ln S_{it}^d + \alpha_i^{G7}\, G7 \ln S_{it}^d + \alpha_i^f (M_{it}/Y_{it}) \ln \left(\frac{S_{it}^f}{S_{i,1985}^f}\right) + v_{it}$$

$$= \alpha_i^0 + \alpha_i^d \ln S_{it}^d + \alpha_i^{G7}\, G7 \ln S_{it}^d + \alpha_i^f (M_{it} / Y_{it}) \ln S_{it}^f - \alpha_i^f (M_{it}/Y_{it}) \ln S_{i,1985}^f + v_{it}\,.$$

The last regressor on the RHS of this expression cannot be incorporated into the constants because it varies with time. In general, the index number transformation will cause coefficient estimates from equations (2) and (3) to be biased.

LP examine measures of both the inward and outward ("technology sourcing") flows of foreign direct investment (FDI). In accord with Coe and Helpman, they

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10 The human capital variable is, however, only significant if it is interacted with the productivity catch-up variable.

11 The criticism of Coe and Helpman's method for calculating a foreign R&D capital stock is not general. It concerns the issue of potential mergers between countries. The issue of mergers is important because Coe and Helpman's study only includes West Germany, yet any updated study of R&D spillovers will have to consider the reunified Germany.

find that the domestic R&D capital stock's elasticity is significantly positive and larger for the G7 economies. The results suggest that while outward FDI is a significant way for the foreign R&D capital stock to spillover, contrary to expectations, the inward flow of FDI is not. The inclusion of the FDI channel for spillovers reduces the elasticity of TFP with respect to the domestic R&D capital stock and reduces the implied average rates of return. The returns to domestic R&D capital were calculated as 51% for the G7 and 63% for six smaller industrialised economies.[12]

While Lichtenberg and van Pottelsberghe de la Potterie examine the import *share* effect, Keller (1997) pays more attention to the import *composition* effect. Keller uses Monte Carlo simulation techniques to construct 1000 random bilateral share matrices. These matrices are used to show that, on average, counterfactual bilateral shares provide a better explanation of productivity levels and indicate greater international R&D spillovers than the corresponding Coe-Helpman equations. The simulated bilateral trade matrices allow the measure of foreign R&D stocks to be *better* at explaining TFP than it is when using the actual bilateral shares. This implies that it is not possible to use Coe and Helpman's original findings to make conclusions about the validity of endogenous innovation models. The actual composition effect makes foreign R&D stocks, on average, worse predictors of TFP than purely randomised composition effects, so R&D spillovers do not seem to be systematically predictable on the basis of the composition of trading partners.

Finally, in a new study of the G7 and seven other industrialised countries, Edmond (1998) has shown that consideration of alternative measures of productivity can produce substantially lower, though still positive, estimates of R&D spillovers. Edmond uses a "rule of thumb" TFP variable, a standard TFP variable equivalent to that used by Coe and Helpman and a new multifactor measure of productivity, total technological productivity (TTP), introduced by Bernard and Jones (1996). Correcting for the mis-specification bias identified by LP produces revised estimated spillovers from the G7 of between 2 and 9%, depending on which of the three productivity measures is used. Tables 2 and 3 summarise the findings from Edmond (1998) calculated for the year 1990. The policy implications of these results are canvassed in section 3.

It should be noted that the macroeconomic studies produce estimates of rates of return and R&D spillovers consistently larger than those obtained from equivalent microeconomic approaches. For example, input-output approaches to R&D spillovers tend to indicate that the rate of return to R&D undertaken by a firm is around 20 to 30%, with the social return to R&D at around 50% (Nadiri 1993: 19-22). Econometric studies of the effects of R&D on cost and production structures

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12 To some extent, Coe and Helpman anticipated this, warning that they place more reliability on the elasticity estimates than they do on the rate of return estimates, and arguing that the results should be seen as "indicative of the importance of R&D" (1995: 874).

TABLE 2

OWN AND WORLD RATES OF RETURN TO R&D CAPITAL, 1990

Measure	TFP*		TFP		TTP	
Country	Own	World	Own	World	Own	World
USA	0.372	0.392	0.927	0.945	0.323	0.354
JPN	0.506	0.548	1.261	1.300	0.440	0.505
DEU	0.419	0.455	1.043	1.077	0.364	0.420
FRA	0.523	0.544	1.303	1.323	0.454	0.487
ITA	1.257	1.273	3.131	3.146	1.092	1.116
GBR	0.402	0.419	1.001	1.017	0.349	0.376
CAN	1.196	1.228	2.977	3.009	1.039	1.090
AUS	2.209	2.213	6.335	6.338	1.999	2.003
BEL	0.654	0.666	1.875	1.887	0.592	0.611
DNK	1.058	1.061	3.034	3.037	0.957	0.962
FIN	1.039	1.041	2.978	2.981	0.940	0.944
NLD	0.529	0.544	1.517	1.531	0.479	0.503
NOR	0.901	0.905	2.584	2.588	0.815	0.821
SWE	0.465	0.472	1.333	1.339	0.420	0.431
Averages						
G7	0.445	0.469	1.072	1.130	0.386	0.424
Other	0.786	0.796	2.255	2.264	0.711	0.726

Source: Edmond (1998: 20).

indicate more variety in the magnitudes of both social and own returns to R&D investment. Net of depreciation, own returns are approximately 12% in R&D-intensive industries while social returns vary between 14 and 25% for R&D-intensive industries and are around 20% for R&D investments in other industries (Nadiri 1993: 23-6).[13]

3. POLICY IMPLICATIONS

The broad conclusion from the new findings of Edmond (1998) is that the use of the measure of TFP which corresponds to that used by Coe and Helpman (just denoted "TFP"), still provides estimates of international R&D spillovers which roughly accord with the original findings. However, there are two important differences that result from the correction of the unwarranted index number transformation. First,

[13] Jones and Williams (1997) survey this literature in a slightly different context. Although they note that microeconomic studies provide estimated own returns of between 30 and 100%, they also show that the optimal social rate of return to R&D investment is closer to 120%. If studies that show actual returns as low as 12 or 14% (as reported by Nadiri (1993)) are correct, then there is massive under-investment in R&D. These results almost exclusively refer to the US.

TABLE 3

R&D SPILLOVERS BASED ON THREE DIFFERENT MEASURES OF PRODUCTIVITY, 1990

Country	Measure		
	TFP*	TFP	TTP
USA	1.053	1.020	1.095
JPN	1.082	1.031	1.148
DEU	1.086	1.032	1.154
FRA	1.040	1.015	1.073
ITA	1.012	1.005	1.023
GBR	1.042	1.016	1.076
CAN	1.027	1.010	1.049
AUS	1.001	1.000	1.002
BEL	1.019	1.007	1.032
DNK	1.003	1.001	1.006
FIN	1.002	1.001	1.004
NLD	1.029	1.009	1.050
NOR	1.004	1.001	1.007
SWE	1.015	1.005	1.025
Averages			
G7	1.055	1.021	1.099
Other	1.012	1.004	1.021

Source: Edmond (1998: 22).

the own rates of return in R&D-scarce economies are generally higher than the returns paid in the R&D abundant G7 economies. This hints that there are diminishing returns to R&D accumulation. The rate of return figures in Table 2 closely accord with scarcity approaches to factor pricing (the factor-proportions theory of international trade would lead us to expect the price of R&D capital to be highest in R&D capital-scarce economies). The long run own returns to the other seven smaller economies average 2.26 dollars per dollar of investment (i.e., 226%). Australia is notable in this respect, paying, on Coe and Helpman's TFP measure, own returns of 6.33 dollars for every dollar of investment in R&D capital. On this measure, it is also notable that the US pays the lowest long run returns (0.93 dollars for every dollar of investment). However, the factor-proportions approach does not account for all of the variability in returns, since the own return in Italy, 3.13, is substantially higher than some of the returns in relatively small economies like Belgium, Finland and Sweden. Yet in general, it seems that economies that are smaller, "younger" and relatively less open to imports pay higher returns to their scarce R&D capital. Other things equal, countries that are younger have less accumulated R&D capital, and countries that are less open to imports have smaller stocks of *effective* R&D capital, since they have less access to the stocks of their trading partners.

Figures 3 and 4 present an informal analysis of the own returns to effective R&D capital to illustrate this argument. Figure 3 shows a scattergram of the long run own returns according to the TFP measure of productivity[14] against a simple sum of domestic and foreign R&D capital, $S_{it}^{s} = S_{it}^{d} + S_{it}^{f}$, for the year 1990. This scattergram shows that Australia is a noticeable outlier. Australia's implied own returns are much higher than its simple stock of effective R&D capital would lead one to predict. However the simple sum, S_{it}^{s}, only takes account of the import composition effect.[15] That is, Australia's own returns are higher than would be expected given the joint effects of (1) Australia's small domestic R&D capital stock and (2) the fact that Australia primarily trades with countries that have large domestic R&D stocks (like the USA and Japan), resulting in a large foreign R&D stock. In effect, it would be expected that the import composition effect should dominate Australia's domestic stock and produce lower returns to Australia's effective R&D stock. However, when account is made of the import share effect, Australia's outlier status largely disappears. Figure 4 shows a scattergram of the own returns against a weighted sum of R&D capital, $S_{it}^{w} = S_{it}^{d} + (M_{it}/Y_{it})S_{it}^{f}$. Weighting Australia's high foreign R&D stock by its relatively low import share gives a more accurate picture of Australia's effective R&D capital stock since it considers the extent to which Australia is "taking advantage" of the external R&D potentially available to it. Once this weighting is done, it is clear that the scarcity of domestic R&D capital dominates the total effect of external sources of accumulated R&D expenditures. Figure 4 provides strong support for the idea that there are slowly *diminishing* returns to R&D capital stocks, but that the absolute *levels* of returns are still very high even for the USA. Figures 5 and 6 show alternative measures of R&D stocks for each of the 14 countries considered by Edmond (1998) for 1990 (the last sample year).

The second implication from Edmond (1998) is that the use of constant-dollar values for R&D stocks, rather than the mis-specified indices, indicates that the size of R&D spillovers is substantially smaller. Using the TFP measure, only about 2 per cent of the total benefit from G7 investment in R&D accrues to its trading partners, not the 25 per cent reported by Coe and Helpman (1995: 874). Systematically, the spillovers from the other OECD economies to their trading partners are smaller than the spillovers from the G7 economies. Another notable feature is that every country in the sample benefits from R&D investment undertaken by its trading partners.[16]

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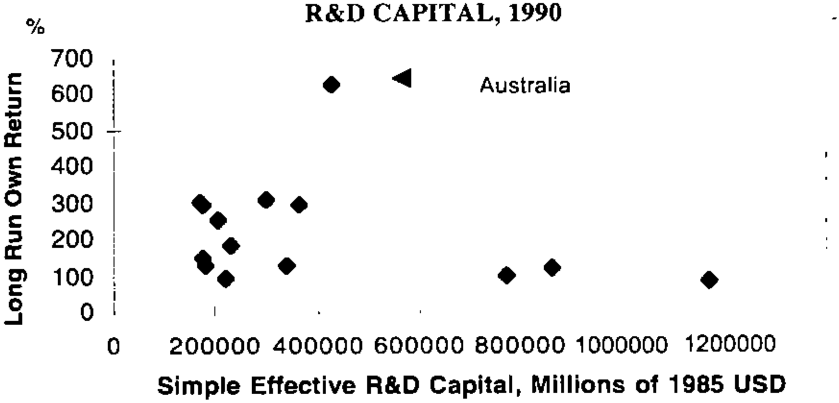
14 The patterns shown in the scattergrams are identical irrespective of which measure of productivity is used. Only the levels of returns on the y-axis change.

15 The simple sum variable measures a "potential" effective R&D capital stock.

16 The results reported for the G7 are commensurate with those from the other studies discussed above, since the same seven countries are involved. However, the results for the "other" countries in the sample will differ from Coe and Helpman's (1995) and LP's (1996) "other" categories since slightly different sub-samples of industrialised countries are involved.

FIGURE 3

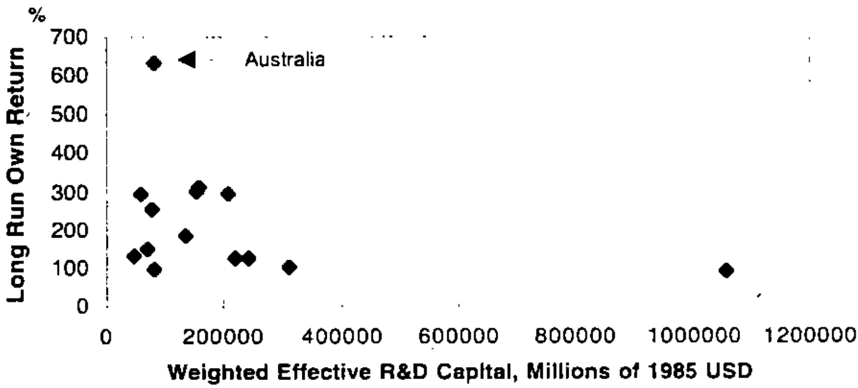
OWN RETURNS AND A SIMPLE MEASURE OF EFFECTIVE R&D CAPITAL, 1990



Source: simple sum of domestic and foreign R&D capital in 1990 against the long run own returns to R&D capital reported in Table 2. The own returns are based on the TFP measure of multifactor productivity with capital shares varying across countries but not over time.

FIGURE 4

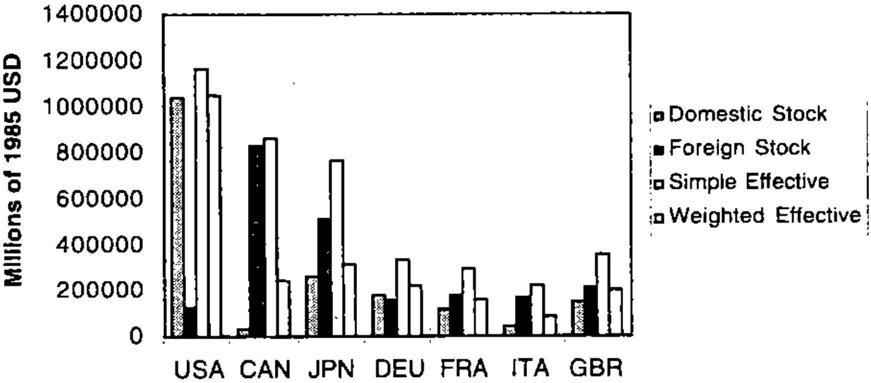
OWN RETURNS AND A WEIGHTED MEASURE OF EFFECTIVE R&D CAPITAL, 1990



Source: weighted sum of domestic and foreign R&D capital in 1990 against the long run own returns to R&D capital reported in Table 2. The weights used are import shares with the total import data taken from the International Monetary Fund's *Direction of Trade Statistics* and the national income data taken from the OECD's *Intersectoral Database*. The own returns are based on the TFP measure of multifactor productivity with capital shares varying across countries but not over time.

FIGURE 5

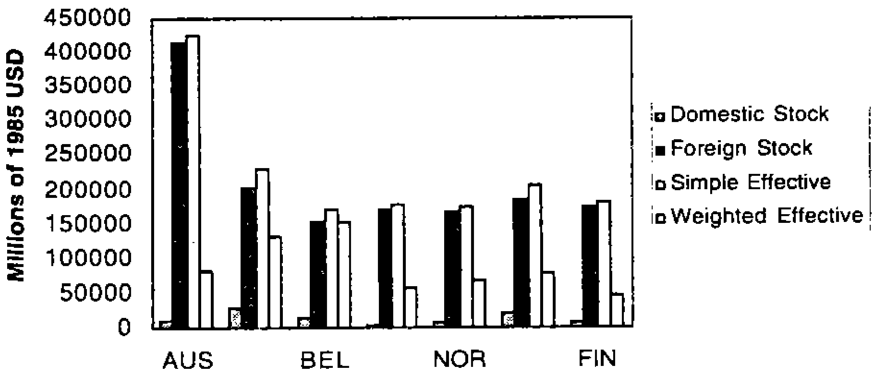
ALTERNATIVE MEASURES OF R&D CAPITAL, G7 COUNTRIES, 1990



Source: construction of these four measures of R&D capital stocks is described in the notes to Figures 1 to 4 and in Edmond (1998: 5-6).

FIGURE 6

ALTERNATIVE MEASURES OF R&D CAPITAL, OTHER COUNTRIES, 1990



Source: construction of these four measures of R&D capital stocks is described in the notes to Figures 1 to 4 and in Edmond (1998: 5-6).

The alternative measures of productivity report similar patterns of rates of returns and spillovers, but the absolute numbers obtained are quite different. Estimated rates of return are generally smaller than those found by using the TFP measure, and although they are still smaller than the original Coe and Helpman findings, the estimated international R&D spillovers found by using TTP or the constrained TFP* are larger than those estimated using TFP.[17] For example, the TTP measure shows a 10% average spillover from the G7 countries to their trading partners, which is smaller than the 25% original estimate produced by Coe and Helpman and larger than the 2% revised estimate obtained by Edmond (1998). The rates of return and spillovers found using TTP and TFP* accord more closely with the foreign direct investment approach of LP (1996) and the human capital approach of Engelbrecht (1997). In general, the rate of return findings using the TTP measure are still higher than the microeconomic results surveyed in Nadiri (1993) and Jones and Williams (1997), but are much closer to the micro findings than the numbers originally obtained by Coe and Helpman (1995).

The extent to which the benefit from investment in R&D spills across national boundaries is of considerable importance in considering the policy implications of endogenous innovation approaches to the theory of economic growth. If the benefits of R&D expenditure accrue almost entirely to the economies that undertake such investment, then the open economy versions of such models tend to predict that convergence in national incomes per capita will be very slow, if it occurs at all.

The results discussed above have two main implications. The first is that increased openness does increase the domestic productivity of industrialised countries. Increased openness of a country to imports from economies that invest in R&D increases the effective stock of R&D capital available to that country and this has a beneficial impact on the productivity of the domestic economy. This has no detrimental impact on the productivity of the trading partners. These results pertain to the aggregate economy, and it is not clear what effect increased openness or economic integration would have on the distribution of income within an economy. Informally, it may be presumed that Stolper-Samuelson effects would distribute income in favour of the owners of an economy's abundant resource and way from the owners of scarce resources (Wong 1995).

The second major implication results from the possibility that rates of returns to R&D capital are distributed in accordance with factor proportions theory. If there are diminishing returns to R&D capital accumulation, then the "scale effect" used by endogenous innovation models is insufficient to generate sustained growth. In

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17 The measure of productivity denoted TFP* is a "rule of thumb" TFP measure calculated by constraining each country's labour share to be the same over the entire time frame. Coe and Helpman's TFP measure allows labour's share to vary across countries but not through time. The TTP measure allows labour's share to vary in accordance with the data. See Bernard and Jones (1996) for further detail on TTP and see Edmond (1998) for more information on the construction of the data series discussed in the text.

this situation, level effects like economic integration or trade liberalisation would only raise the rate of an economy's growth in the transition path, not in the steady state. Of course, transitional growth may be a more important and more interesting phenomena than steady-state growth. Since the transitional rate of growth can be raised, and since long transition paths are a feature of endogenous growth models with less than perfect capital mobility, "semi-endogenous" growth is still possible (Jones 1995a,b, Young 1995).[18]

4. SOME CAUTIONARY REMARKS

The data sets used in studies of international R&D spillovers are examples of panel data. For a given set of "individuals" in the cross section, there exist a number of time series observations. In this case, the time-series of only 20 or so annual observations would normally rule out individual unit root and cointegration tests as a practical consideration. Although Coe and Helpman performed individual ADF tests, they did not attach any meaning to the results from the tests.[19] Coe and Helpman estimated their equations in levels, arguing that:

> Given these mixed results, and given that the econometrics of pooled cointegration are not yet fully worked out, we place more emphasis on consistency with the theoretical model and on the a priori plausibility of the estimated parameters than on the tests for cointegration.

Edmond (1998) has re-examined the time series properties of the relevant data sets. Using a new and relatively powerful panel unit root test provided by Im, Pesaran and Shin (1997), he shows that Coe and Helpman's intuition is correct. Irrespective of which of three productivity measures is used, at least one cointegrating relationship can be found between the R&D stock series and productivity. Although the issue of cointegration has largely been resolved, a couple of problems remain. These concern the consistency of pooled estimators for panel data and the direction of causality.

Having observations on a cross-section of individuals allows dramatic power improvements over conventional procedures, since the stochastic process (which is hypothesised to differ only by parameters) can be "observed" many times. Despite these advantages, the analysis of panel data has typically proceeded via one of four methods. Data can be *pooled* (as Coe and Helpman do), coefficients of individual regressions can be *averaged* to provide "mean group estimators," the

18 Recall Bayoumi et al's (1996) simulation finding that sustained increases in the level of R&D investment over long periods were required to produce changes in growth rates. Jones (1995a,b) acknowledges that it may still be too soon to see any rate effects from the changes in R&D levels that he documents.

19 As for panel unit roots, according to the Levin and Lin (1992, 1993) tests Coe and Helpman's equations may or may not be cointegrating, depending on whether the dynamic specifications are constrained to be the same across all of their 22 sample countries. See Quah (1994), Levin and Lin (1992, 1993), and Im, Pesaran and Shin (1997) for further details on panel data unit root tests.

data can be averaged over individuals in the cross-section to form a single time series, or the data can be averaged over time to provide a single cross-section.

Under certain conditions, each of the four procedures produces equivalently consistent/unbiased estimates of the coefficient means. However, in a dynamic panel setting, these procedures do not, in general, produce consistent/unbiased estimators (Pesaran and Smith 1995: 79-81). In particular, the pooled estimators used by Coe and Helpman (1995), LP (1996), Engelbrecht (1997) and Edmond (1998) may be inconsistent in dynamic heterogeneous panel settings. Unless the population parameters are identical across individual countries, the obtained regression coefficients do not necessarily converge in large samples to the true parameters. The rates of return and spillovers findings based on the obtained coefficients may be misleading.

A final issue in the econometrics of R&D spillovers concerns the direction of causality. A number of commentators on Coe and Helpman's original findings have noted the presumption that causality runs from accumulated R&D expenditures to productivity (Dowrick 1995, Barro and Sala-i-Martin 1995). It is likely that, to some extent, increased productivity makes higher expenditure on R&D possible. Certainly, this is part of the explanation offered by Jones (1995a,b) when he noted that increased levels of resources devoted to science and technology did not correlate with increased rates of economic growth. The provision of consistent pooled estimates of rates of returns and serious confrontation of causality issues remain the most immediate econometric tasks confronting the R&D spillovers literature.

5. SUMMARY AND CONCLUSIONS

The macroeconomic approach to international R&D spillovers has allowed a number of the implications of endogenous innovation growth models to be empirically scrutinised. This attention is overdue. However, before too much emphasis is placed on this new literature, several important issues must be addressed. Most importantly, the high rates of return and large spillovers found in the macroeconomic literature need to be reconciled with the smaller returns and spillovers documented by microeconomic studies. To some extent, the revised estimates provided by Lichtenberg and van Pottelsberghe de la Potterie (1996), Engelbrecht (1997) and Edmond (1998) have done this. The rates of returns (of around 50 and 60%) in these macro approaches are much closer to the upper bounds of the findings of micro studies than are Coe and Helpman's estimates. The revisions to Coe and Helpman's original method show that international R&D spillovers are still qualitatively important, but are considerably smaller than may have originally been thought.

Two important econometric issues remain, however. First, the estimates derived from the studies discussed in this paper ignore the problems inherent in pooling panel data. Until consistent pooled estimates are provided, the strength of any conclusions drawn from this literature must remain heavily qualified. Second, the question of causality remains unanswered; despite the fact that this was the immediate substantial criticism made of Coe and Helpman's method. Again, policy recommendations require stronger evidence that the direction of causality runs from R&D to productivity. It seems likely, as an intuitive proposition, that bi-directional causality exists. Causality considerations are particularly important given Jones' (1995b) finding that increased levels of investment in R&D-like activities do not have simple consequences for productivity.

Jones' (1995a,b) findings indicate that the relationship between investment in activities like R&D and productivity may be similar to the relationship between savings and output growth in the Solow model. Increasing the fraction of resources devoted to R&D accumulation appears to only have transitional effects on the rate of productivity growth in the short run and to have no effect on productivity growth in the long run. This evidence of diminishing returns to R&D accumulation is supported by the findings of Edmond (1998) discussed above. There is quite strong evidence that the returns to R&D capital stocks are distributed in a manner roughly consistent with factor proportions trade theory. R&D capital-scarce countries like Australia tend to pay distinctly higher returns than R&D capital-abundant countries like the United States. The revised studies of international R&D spillovers discussed in this paper do not contradict Jones' tests of the "scale effects" prediction of endogenous innovation models. So far, the evidence from research on international R&D spillovers gives more support to recent semi-endogenous growth models than it does to the first wave of endogenous innovation theories.

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