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International R&D spillovers

David T. Coe [a], Elhanan Helpman [b,c,*]

[a] *International Monetary Fund, Washington DC, USA*
[b] *The Eitan Berglas School of Economics, Tel Aviv University, Tel Aviv 69978, Israel*
[c] *Canadian Institute for Advanced Research, Toronto, Canada*

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Abstract

A model is presented based on recent theories of economic growth that treat commercially oriented innovation efforts as a major engine of technological progress. We study the extent to which a country's total factor productivity depends not only on domestic R&D capital but also on foreign R&D capital. Our estimates indicate that foreign R&D has beneficial effects on domestic productivity, and that these are stronger the more open an economy is to foreign trade. Moreover, the estimated rates of return on R&D are very high, both in terms of domestic output and international spillovers.

Keywords: Productivity; R&D; Spillover

JEL classification: O31; O40

1. Introduction

Economic growth has many facets. It depends on the utilization of resources, the rate of population growth, the savings rate, the mode of organization of economic activity, technological know how, and more. Whereas the neoclassical theory treated technological progress as an exogenous process and focused instead on capital accumulation as the main endogenous source of output expansion, recent research has provided novel ways of dealing with technological progress. The

* Corresponding author.

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latter studies view commercially oriented innovation efforts that respond to economic incentives as a major engine of technological progress and productivity growth (see Romer, 1990; Grossman and Helpman, 1991). In this view, innovation feeds on knowledge that results from cumulative R&D experience on the one hand, and it contributes to this stock of knowledge on the other. Consequently an economy's productivity level depends on its cumulative R&D effort and on its effective stock of knowledge, with the two being inter-related. There exists, in fact, convincing empirical evidence that cumulative domestic R&D is an important determinant of productivity (see Griliches, 1988; Coe and Moghadam, 1993).

In a world with international trade in goods and services, foreign direct investment, and an international exchange of information and dissemination of knowledge, a country's productivity depends on its own R&D as well as on the R&D efforts of its trade partners. Own R&D produces traded and nontraded goods and services that bring about more effective use of existing resources and thereby raises a country's productivity level. In addition, own R&D enhances a country's benefits from foreign technical advances, and the better a country takes advantage of technological advances in the rest of the world the more productive it becomes. The benefits from foreign R&D can be both direct and indirect. Direct benefits consist of learning about new technologies and materials, production processes, or organizational methods. Indirect benefits emanate from imports of goods and services that have been developed by trade partners. In either case foreign R&D affects a country's productivity.

We study in this paper the extent to which a country's productivity level depends on domestic and foreign R&D capital stocks. Following much of the theoretical and empirical literature, we use cumulative R&D expenditure as a proxy for a stock of knowledge. For every country in our sample we construct a stock of domestic knowledge that is based on domestic R&D expenditure and a foreign stock of knowledge that is based on R&D spending of its trade partners. For the construction of foreign R&D capital stocks we use import weighted sums of trade partner's cumulative R&D spending. [1] We explain the rationale for this procedure in the theoretical section. For every country we also calculate a measure of total factor productivity defined as the log of output minus a weighted average of the logs of labor and capital inputs, where the weights equal factor shares. Having done these calculations, we estimate the effects of domestic and foreign R&D capital stocks on total factor productivity. Our estimates underline the importance of the interaction between international trade and foreign R&D.

Our sample consists of 21 OECD countries plus Israel during the period 1971–90. We find, using pooled time series cross section data, that both domestic and foreign R&D capital stocks have important effects on total factor productivity. Some of our estimates suggest that foreign R&D capital stocks have stronger effects on domestic productivity the larger the share of domestic imports in GDP. It follows that more open economies extract larger productivity benefits from foreign R&D than less open economies. Moreover, measuring the importance of the R&D capital stock by the elasticity of TFP with respect to the R&D capital stock, our estimates suggest that the foreign R&D capital stock may be at least as important as the domestic R&D capital stock in the smaller countries, while in the larger countries (the G7) the domestic R&D capital stock may be more important.

[1] This is analogous to Terleckyj's (1974) use of input-output weights to model how R&D is imported across industries.

The next section contains a discussion of the theory that underlies our empirical specification. A brief review of the main features of our data is presented in Section 3, and the sources and construction of the data are described in an appendix. The main empirical findings and their economic interpretations are reported in Section 4. Section 5 concludes.

2. Theory

Our empirical equations build on some recent theoretical models of innovation-driven growth. Since the basic models of this theory have been widely discussed, we provide in this section only rudimentary details and focus instead on results that are needed for our purpose. The reader is referred to Helpman (1992) for a review and to Grossman and Helpman (1991) for a detailed description of the models on which we base our discussion.

In the simplest case, an economy manufactures final output Y from an assortment of intermediate inputs. Given the measure of available intermediate inputs n, the production function of final output is a linear homogeneous function of the employed inputs. Two stories appear to be common in the formulation of the production function. In one case the inputs are horizontally differentiated. A simple formalization of this view takes the production function to be a symmetric constant elasticity of substitution function, with the elasticity of substitution being larger than one and every input to be manufactured with a unit of labor per unit output. The result is that output is proportional to aggregate employment of intermediates, or to total labor employed in the manufacturing of intermediates. And most importantly, the factor of proportionality is an increasing function of the measure of available inputs n.

The measure of available inputs expands as a result of R&D investment. Entrepreneurs who seek monopoly profits invest resources in the development of new intermediate inputs. In this event the measure of available inputs is an increasing function of the country's cumulative R&D effort. It follows that the log of total factor productivity (TFP), as measured by $\log Y - \log L$ (where L stands for the available labor force and no capital is used in production), depends on a measure of cumulative R&D and the share of labor employed in manufacturing. In this model labor is employed either in manufacturing or in R&D. Therefore as long as R & D is a small share of GDP that does not differ greatly across countries and time periods (as it is in our sample where R & D expenditures average about 1.5 percent of GDP with a maximum of about 2 percent), the fraction of labor employed in production is very close to one and remains approximately constant. In this case we expect differences in cumulative R & D to explain most of the variation in TFP.

An alternative model treats intermediate inputs as vertically differentiated; namely, they come in different qualities. Here the effectiveness of an input in manufacturing depends on the number of times it has been improved, and inputs that have been improved more times are more productive. Entrepreneurs invest in research and development to improve inputs. In this model, the average productivity of all inputs depends on cumulative past R & D spending. As a result, this model too implies that total factor productivity is rising with the cumulative R & D effort.

These two examples have disregarded capital and international trade. As for capital, Grossman and Helpman (1991) have shown in Chapter 5 that the presence of capital accumulation does not change the fact that TFP is an increasing function of cumulative R & D, except that with capital as an additional factor of production, $\log TFP$ has to be defined in the usual way as $\log Y - \beta \log K - (1-\beta)\log L$, where β is the share of capital in GDP.

Next consider international trade. The previous arguments apply in the absence of international trade in intermediate inputs, regardless of whether final output is traded or not. If this was the relevant case, we would be able to explain variations in a country's total factor productivity with variations in its domestic R & D capital stock. Most international trade takes place in producer goods, however. In this event countries use extensively inputs that are manufactured by trade partners and inputs that were developed by trade partners. How does this change our conclusions?

In order to see as clearly as possible the role of international trade, consider an extreme case in which all intermediate inputs are traded internationally. Under these circumstances our basic relationship between total factor productivity and cumulative R & D remains valid, except that the relevant measure of R & D capital is not the individual country's R & D capital stock, but rather the entire *world's* R & D capital stock. When a country has free access to all inputs available in the world economy, its productivity depends on the world's R & D experience, because independently of where an input has been developed or improved the country can purchase the input and employ it in manufacturing. In this extreme case, domestic R & D has the same productivity effects as foreign R & D.

For empirical implementations of these models neither one of the extreme specifications of tradeability of intermediate inputs seems appropriate; there exist many tradeable inputs, but nontradeable inputs of goods and services are also prevalent. It is therefore most practical to formulate an empirical equation that allows for both traded and nontraded inputs. For these reasons we estimate

equations in which variations in TFP are explained by variations in both the domestic and foreign R & D capital stocks. Our simplest equation has the following specification:

$$\log F_i = \alpha_i^0 + \alpha_i^{\mathrm{d}} \log S_i^{\mathrm{d}} + \alpha_i^{\mathrm{f}} \log S_i^{\mathrm{f}}, \qquad (1)$$

where i is a country index, $\log F$ is the log of total factor productivity (equal to $\log Y - \beta \log K - (1-\beta)\log L$), S^{d} represents the domestic R & D capital stock, and S^{f} represents the foreign R & D capital stock defined as the import-share-weighted average of the domestic R & D capital stocks of trade partners. In this specification we allow the coefficients α to vary across countries. In the implementation, however, we will seek cross-country restrictions on the elasticities α^{d} and α^{f}.[2] The specification of (1) can be thought of as a multicountry extension of models relating TFP to only the domestic R & D capital stock, which would be a special case with $\alpha^{\mathrm{f}} = 0$.

The specification of (1) may not capture adequately the role of international trade. Although, the foreign stock of knowledge S^{f} consists of import weighted foreign R & D capital stocks, these weights are fractions that add up to one and therefore do not properly reflect the *level* of imports. It might be expected that whenever two countries have the same composition of imports and face the same composition of R & D capital stocks among trade partners, the country that imports more relative to its GDP may benefit more from foreign R & D. This is in line with the theoretical arguments presented above and can be strengthened with additional arguments that relate productivity gains to trade volumes (see Grossman and Helpman, 1991, Section 6.5). For these reasons a modified specification of (1) that accounts for the interaction between foreign R & D capital stocks and the level of international trade seems preferable. To this end we estimate

$$\log F_i = \alpha_i^0 + \alpha_i^{\mathrm{d}} \log S_i^{\mathrm{d}} + \alpha_i^{\mathrm{f}} m_i \log S_i^{\mathrm{f}}, \qquad (2)$$

where m stands for the fraction of imports in GDP. In this equation the elasticity of TFP with respect to the domestic R & D capital stock equals α^{d} while the elasticity of TFP with respect to the foreign R & D capital stock equals $\alpha^{\mathrm{f}} m$. It follows that whenever α^{f} is the same for all countries the latter elasticity varies across countries in proportion to their import shares.[3]

[2] We always allow the constants α° to differ across countries for two reasons: first, there may exist country specific effects on productivity that are not captured by the variables used in our equations; and second, variables are transformed into index numbers and TFP is measured in country specific currencies whereas both R&D capital stocks are in U.S. dollars.

[3] An analogy may help to put our use of import shares in context. In microeconomic studies of technological spillovers it is common to seek a metric, such as 'technological closeness', in order to gauge the intensity of spillovers. Scherer (1982) and Jaffe (1986) provide good examples. In our case it is most natural to use import shares as measures of intensity. This is the more so whenever productivity gains are related to imports of intermediate inputs as exemplified by the theoretical model.

Table 1
Summary statistics

	F_{1990}/F_{1971}	$S^{d}_{1990}/S^{d}_{1971}$	$S^{f}_{1990}/S^{d}_{1971}$	m (in percent)	
				1971	1990
United States	1.1	2.0	3.4	5.5	11.2
Japan	1.7	4.2	1.7	9.6	9.3
West Germany	1.2	2.6	1.6	19.1	26.1
France	1.4	1.8	1.7	15.3	22.8
Italy	1.4	2.8	1.4	15.6	19.6
United Kingdom	1.3	1.3	1.8	21.4	27.7
Canada	1.1	2.7	1.9	20.0	25.5
Australia	1.1	4.9	2.0	14.7	18.6
Austria	1.2	3.6	2.3	30.8	38.9
Belgium	1.4	2.3	1.5	43.9	88.2
Denmark	1.2	2.3	1.9	30.9	31.1
Finland	1.4	4.5	2.2	26.8	25.4
Greece	1.2	18.7	1.7	17.0	32.0
Ireland	1.3	3.7	2.3	42.1	56.1
Israel	1.3	7.3	1.6	50.0	52.0
Netherlands	1.2	1.5	1.9	45.1	53.9
New Zealand	0.9	2.1	2.3	25.5	22.6
Norway	1.5	4.0	2.0	45.3	37.7
Portugal	1.3	2.0	1.4	33.6	44.9
Spain	1.2	7.0	1.2	14.7	21.4
Sweden	1.1	3.5	1.9	22.8	31.6
Switzerland	1.1	1.3	1.9	39.1	38.3

Source: Tables A.1, A.3, A.5, and A.6 in Appendix A.

3. Data

We provide in the appendix details about data sources and the construction of the variables for estimation purposes. Here we only highlight some features of the data. [4] As shown in Table 1, total factor productivity increased over the 1971–90 period in all countries except New Zealand. But the upward trend was neither uniform across countries nor uniform over time. Japan and Norway experienced the largest increase in productivity of about 70 and 50 percent, respectively; while in New Zealand productivity actually declined. Other countries had intermediate values. Fig. 1 provides plots of TFP for six of these countries; they clearly exhibit substantial fluctuations.

[4] The data used to construct TFP for a number of countries have been revised during the period since our database was established; a preliminary examination of the estimation results based on the updated TFP data indicates that our central conclusions are unchanged.

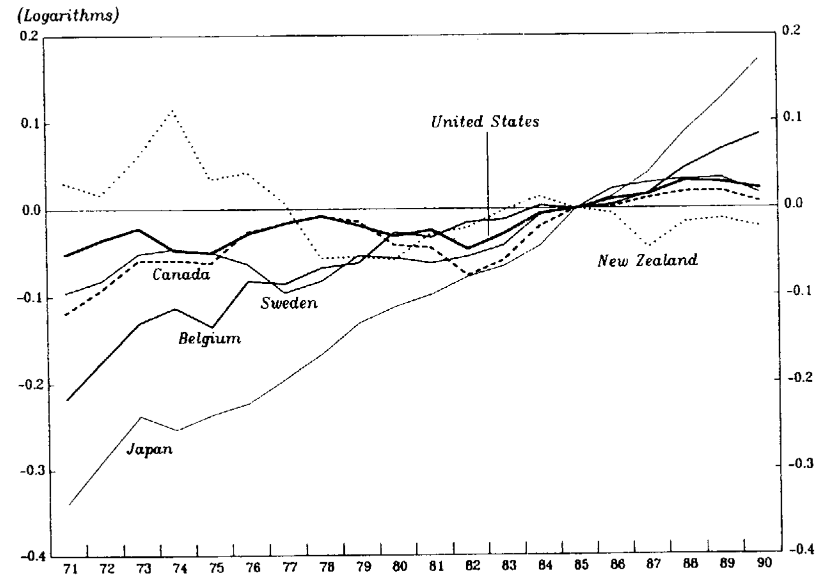

Fig. 1. Total factor productivity.

Between 1971 and 1990 the domestic R&D capital stock increased significantly in most countries. In Greece in particular it increased by a factor of 19, but this is an exception. [5] In Israel and Spain this stock was sevenfold larger by the end of the period than at the beginning, and it had more than quadrupled in Japan, Australia, Finland, and Norway. The United Kingdom and Switzerland experienced the slowest expansion of their domestic R&D capital stock of 20 and 30 percent, respectively. An important point to observe, however, is that the annual changes in this R&D capital stock were not uniform across countries, as can be seen from Fig. 2.

Overall changes in foreign R&D capital stocks were less dramatic than in the domestic R&D capital stocks. Here the United States experienced the fastest expansion: more than threefold. Spain faced the smallest increase of only 20 percent. Other countries enjoyed a doubling of their foreign R&D capital stocks with some variance around this figure. Fluctuations in the foreign R&D capital stocks around their time trends appear to be larger than for the domestic R&D

[5] The level and growth of the R&D capital stocks are sensitive to the assumed depreciation rates and the calculated benchmarks. Table 13 reports estimation results based on a 15 percent rather than a 5 percent depreciation rate.

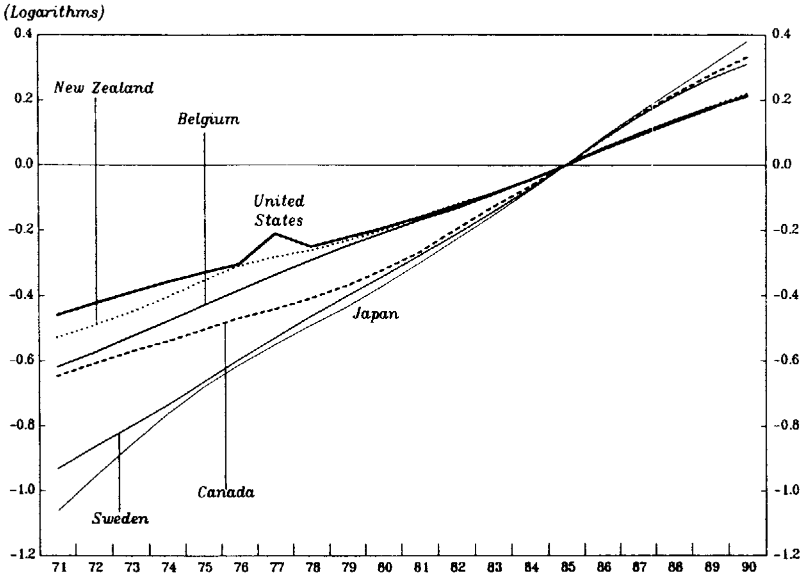

Fig. 2. Domestic research and development capital stocks.

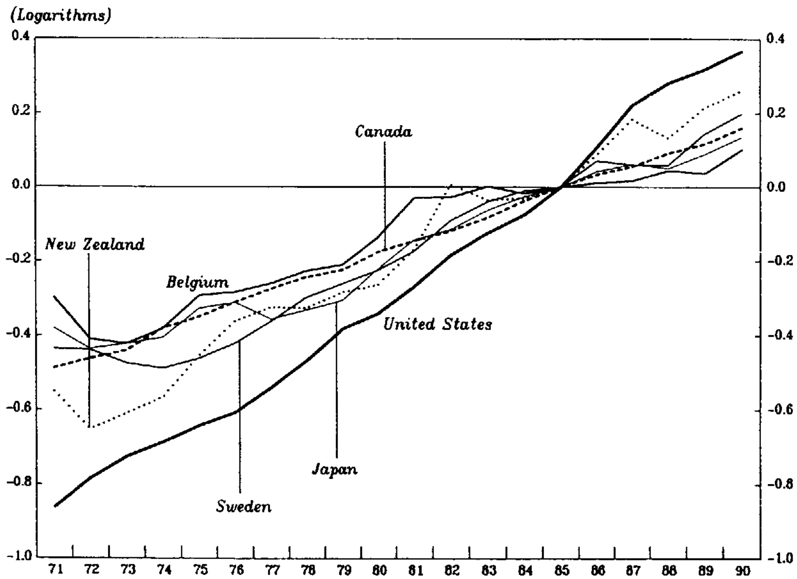

Fig. 3. Trade weighted foreign research and development capital stocks.

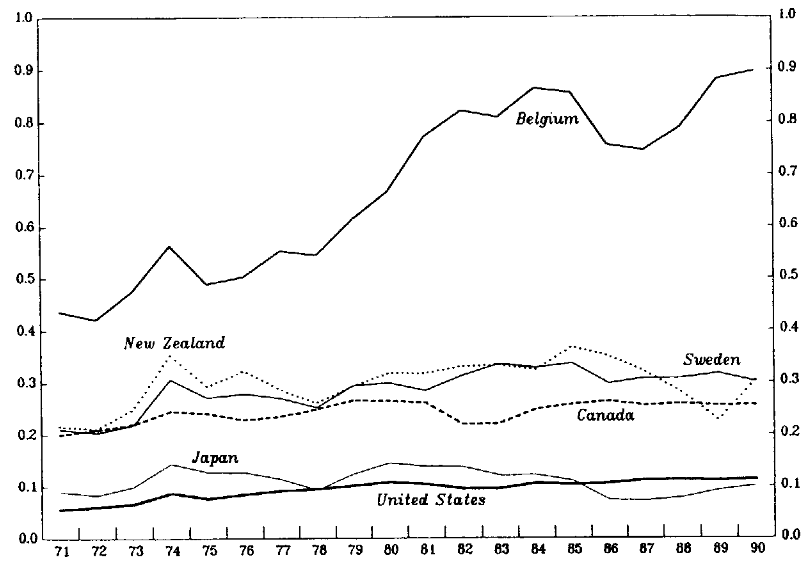

Fig. 4. Import share in GDP.

capital stocks, reflecting the use of bilateral import shares that change from year-to-year, as can be seen by comparing Fig. 3 with Fig. 2.

Finally, Table 1 provides data on import shares. In all countries except for Japan, Finland, New Zealand, Norway, and Switzerland the import share increased between 1971 and 1990. It has more than doubled in the United States and Belgium and only slightly increased in Denmark and Israel. Import shares declined slightly from 1971 to 1990 in Japan, Finland, New Zealand, Norway, and Switzerland. Moreover, there exist substantial differences in import shares across countries. Belgium had by far the largest import share in 1990 (88.2 percent) while Japan had the smallest (9.3 percent). And as shown in Fig. 4, import shares fluctuated over time.

4. Empirical findings

Because almost all of our data exhibit a clear trend, and because we want to estimate the long-run relationship between total factor productivity and the foreign and domestic R&D capital stocks, we seek to estimate equations that are cointegrated. [6] The basic idea of cointegration is that if there is a long-run

[6] Cuthbertson et al. (1992) present a useful survey of cointegration; see also Engle and Granger (1987) and Stock (1987).

Table 2
Pooled unit-root tests (annual data 1972–90 for 22 countries, 418 observations) [a]

	Levin and Lin	
	(1992)	(1993)
log F	−1.85	0.54
log S^d	−0.73	0
log S^f	−2.00	2.58
$m \cdot \log S^f$	−4.07	2.86

[a] The critical values at the 10 percent confidence level are −6.78 for Levin and Lin (1992), and −1.64 for Levin and Lin (1993). F = total factor productivity; S^d = domestic R and D capital stock, beginning of year; S^f = foreign R and D capital stock, beginning of year; m = ratio of imports of goods and services to GDP, both in the previous year.

relationship between two or more trended variables, a regression containing all the variables – the cointegrating equation – will have a stationary error term, even if none of the variables taken alone is stationary. If the error term is not stationary, the estimated relationship may be spurious (Granger and Newbold, 1974).

Most studies of the determinants of total factor productivity or output have been based on a change, rather than a levels, specification because differencing was thought necessary to avoid the spurious correlation problem when estimating a relationship between trended variables. The disadvantage of a change specification is that the information embodied in the long-run relationship between the levels of the variables is discarded by differencing. The advantage of the cointegrating approach, in which the relationship is estimated in level terms, is that it exploits rather than discards the relevant information about shared trends that is embodied in the levels data.

Cointegrated equations have attractive econometric properties. The most important is that as the number of observations increases, OLS estimates of the cointegrating equation converge on the true parameter values much faster than in the case where the variables are stationary, i.e., they are 'super consistent' (Stock, 1987). Cointegration techniques have been widely applied to time-series data. It seems natural to test for international R&D spillovers on panel data, however, and the relatively small number of time-series observations that are available for any single country makes the use of a panel data set particularly attractive. We therefore estimate our equations on panel data and interpret the results as pooled cointegrating equations.

Before turning to the estimation results, we need to confirm that our data are nonstationary. When done separately on the time series for each country, the Dickey–Fuller and the augmented Dickey–Fuller tests generally do not reject the presence of a unit root. As is well known, however, the power of these tests is very low, particularly with only twenty annual observations. Levin and Lin (1992, 1993) have recently derived the limiting distributions for unit root tests on panel data, and have shown that the power of these tests increases dramatically as the

Table 3
Total factor productivity estimation results (pooled data 1971–90 for 22 countries, 440 observations) [a]

	(i)	(ii)	(iii)
log S^d	0.097	0.089	0.078
$G7 \cdot \log S^d$		0.134	0.156
log S^f	0.092	0.060	
$m \cdot \log S^f$			0.294
Standard error	0.049	0.046	0.044
R^2	0.558	0.621	0.651
R^2 adjusted	0.534	0.600	0.630
Cointegration tests:			
Levin and Lin (1992)	−4.533	−9.356	−5.082
Levin and Lin (1993)	0.570	2.201	2.266
t-statistic on the lagged residual in the EC model	−5.451	−6.293	−6.974

[a] The dependent variable is log (total factor productivity). All equations include unreported, country-specific constants. The critical value at the 10 percent confidence level is −6.78 for Levin and Lin (1992), and −1.64 for the other two cointegration tests; test statistics that are negative and greater in absolute value than the critical values indicate that the equations are cointegrated. The EC (error correction) model is the first difference of each equation augmented to include the lagged residual from the equations reported above. S^d = domestic R and D capital stock, beginning of year; S^f = foreign R and D capital stock, beginning of year; $G7$ = dummy variable equal to 1.0 for the seven major countries and equal to 0 for the other 15 countries; m = ratio of imports of goods and services to GDP, both in the previous year.

cross-section dimension increases. [7] Unit root tests on the pooled data confirm that the variables are nonstationary, as shown in Table 2.

We report in Table 3 three pooled cointegrating regressions based on Eqs. (1) and (2). [8] All of the equations include unreported country-specific constants. [9] Equation (i) is the basic specification where the estimated coefficients on the domestic and foreign R&D capital stocks are constrained to be the same for all

[7] The test in Levin and Lin (1992) constrains the dynamics of the augmented Dickey-Fuller to be the same across all countries, whereas the test in Levin and Lin (1993) allows the dynamics to differ across countries.

[8] As is standard practice when reporting cointegrating equations, we do not report standard errors for the estimated coefficients because they are, in general, biased and their distribution is not asymptotically normal. In any event, the estimated standard errors are all small relative to the estimated coefficients (one-fourth or less).

[9] Including the country-specific constants generally makes little difference to the estimated parameters. It does, of course, improve the goodness of fit somewhat: the adjusted R^2 of equation (iii), for example, increases from 0.532 to 0.630 when the country-specific constants are included. This means that the lion's share of the explained variance is due to our R&D capital stock variables rather than to the country-specific constants.

countries. In equation (ii), the impact of domestic R & D is allowed to differ between the largest seven economies compared with the other 15 economies – this is done by interacting the domestic R & D stock with a dummy variable that takes the value of 1 for the seven largest economies (G7) – while constraining the impact of foreign R & D to be the same for all countries. [10] This latter constraint is dropped in equation (iii) where the foreign R & D capital stock is interacted with the ratio of imports to GDP, thereby allowing for country-specific, time-varying elasticities on foreign R & D that are related to trade shares (as discussed above). If the ratio of imports to GDP is included separately as an additional independent variable, the estimated coefficient is negative. Estimation results based on a variety of alternative specifications and testing for parameter stability are reported in Appendix B.

For the estimated equations to be cointegrated, the residuals must be stationary. Equation (ii) is cointegrated based on Levin and Lin (1992), but none of the equations are cointegrated based on Levin and Lin (1993). Engle and Granger (1987) suggest that a test for cointegration is to include the lagged residuals from the cointegrating equations in the corresponding error-correction model and then test whether the estimated coefficient is negative and significantly different than zero. [11] The relevant t-statistics, which are also reported in Table 3, indicate that the error correction terms are significantly different from zero, suggesting that the equations in Table 3 are cointegrated. 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. [12]

The estimated coefficients reported in Table 3 are of the expected sign and the magnitudes of the estimated elasticities are plausible and relatively stable across the different specifications. For the non-G7 countries, the estimated elasticities of TFP with respect to the domestic R & D stock are similar to the 0.06 to 0.1 range typically found in single-country studies (as summarized in Griliches (1988, p. 15)). For the G7 countries, however, the estimated elasticities of TFP with respect to the domestic R & D stock in equations (ii) and (iii) are considerably larger than those from studies that do not include international R & D spillovers. Our cross-country data and estimation procedure that focuses on the identification of long-run relationships may be better able to estimate the social return to R & D compared with studies for individual countries.

In equation (iii), which corresponds to Eq. (2) in the theory section, the impact of the foreign R & D capital stock varies across countries and over time. Table 4 reports the estimated elasticities of total factor productivity with respect to the foreign R & D capital stocks – which are simply the estimated coefficient from Table 3 multiplied by the import share – for 1971, 1980, and 1990. With the notable exceptions of Norway, Spain, and Switzerland, the estimated impact of foreign R & D rises from 1971 to 1980, usually by a substantial amount. In most of the countries, and especially in Belgium, the estimated impact of foreign R & D rises further during the 1980s. Although the domestic R & D capital stock has a

[10] We tested the hypothesis that the coefficient on the foreign R&D stock also differed between the G7 economies compared with the others by adding the foreign R&D stock interacted with the G7 dummy to equation (ii), but the estimated coefficient was very small. The larger impact of domestic R&D on total factor productivity may reflect the fact that large countries perform R&D across a broader range of possible R&D activities, thereby better exploiting available complementarities. This is more likely the slower or the less perfectly R&D results spillover to foreign countries. Tests of whether the estimated slope coefficients are the same across countries are rejected.

[11] Engle and Granger (1987) propose a two-step approach to cointegration. The first step is to estimate the long-run cointegration equation, which corresponds to the equations reported in Table 3. The second step is to estimate the dynamic error-correction model, which is the first difference of the cointegration equation augmented to include the lagged residuals from the cointegration equation as the error-correction term and other stationary variables that are relevant to the short-run dynamics.

[12] Evidence in favor of cointegration is stronger for some of the equations reported in Table 14 of Appendix B, which are based on an output rather than a total factor productivity specification.

Table 4
Country-specific, time-varying estimates of the impact of R&D capital stocks on total factor productivity [a]

	Elasticity of total factor productivity with respect to:				
	World R&D	Foreign R&D			Domestic R&D
	1990	1971	1980	1990	1971–90
United States	0.267	0.016	0.030	0.033	
Japan	0.261	0.028	0.037	0.027	
West Germany	0.311	0.056	0.072	0.077	
France	0.301	0.045	0.061	0.067	0.234
Italy	0.292	0.046	0.067	0.058	
United Kingdom	0.315	0.063	0.081	0.081	
Canada	0.309	0.059	0.078	0.075	
Australia	0.132	0.043	0.049	0.055	
Austria	0.192	0.091	0.106	0.114	
Belgium	0.337	0.129	0.181	0.260	
Denmark	0.169	0.091	0.094	0.092	
Finland	0.152	0.079	0.088	0.075	
Greece	0.172	0.050	0.063	0.094	
Ireland	0.243	0.124	0.180	0.165	0.078
Israel	0.231	0.147	0.154	0.153	
Netherlands	0.236	0.133	0.146	0.158	
New Zealand	0.144	0.075	0.086	0.066	
Norway	0.188	0.133	0.124	0.111	
Portugal	0.210	0.099	0.117	0.132	
Spain	0.141	0.043	0.043	0.063	
Sweden	0.171	0.067	0.087	0.093	
Switzerland	0.190	0.115	0.106	0.113	

[a] Based on equation (iii) in Table 3.

much larger impact on total factor productivity in the large countries compared with the small countries, the smaller countries are more open and hence benefit from foreign R&D more than the larger countries. Indeed, foreign R&D has a larger impact on total factor productivity than does domestic R&D in all of the smaller countries except Australia, Finland, New Zealand, and Spain. Foreign R&D has the strongest impact on Belgium, followed by Ireland, the Netherlands, and Israel.

Estimates of the international R&D spillovers based on equation (iii) are presented in Table 5. Each entry is the estimated elasticity of total factor productivity in the country indicated in the row with respect to the R&D capital stock in the country indicated in the column. [13] Elasticities are largest with respect to the R&D capital stocks of the major countries, because their R&D capital stocks are relatively large and because the major countries account for a relatively high share of other countries' imports, which are used as the weights in the computation of the foreign R&D capital stocks. The estimated R&D spillover elasticities are large. They are largest from the United States and Japan. The estimates imply that a 1 percent increase in the R&D capital stock in these countries increases total factor productivity in their trade partners by an average of 0.04 and 0.01 percent, respectively.

The last row of Table 5 provides average elasticities, taking account of a country's effect on both its own productivity and on the productivity of its trade partners. It shows that a 1 percent increase in the R&D capital stock in the United States raises the average productivity of all 22 countries by about 0.12 percent, while a 1 percent increase in the Japanese R&D capital stock raises the average productivity of the 22 countries by only 0.045 percent. This difference reflects partly the fact that the United States has an R&D capital stock that is about four times as large as Japan's R&D capital stock. Since the elasticity of the United States is less than three times as large as the elasticity of Japan, it follows that the worldwide rate of return on investment in Japanese R&D is larger than the worldwide rate of return on investment in American R&D.

In order to obtain estimates of rates of return on investment in R&D, we need to multiply the elasticities with the appropriate ratios of output to R&D capital stocks. In particular, the rate of return on country j's R&D capital stock in terms of country i's output is

$$\rho_{ij} = \alpha_{ij} \frac{Y_i}{S_j^{\mathrm{d}}}, \tag{3}$$

[13] When the R&D capital stock of country i, S_i^{d}, increases by 1 percent, the foreign R&D capital stock of country j, S_j^{f}, rises by $m_i^j S_i^{\mathrm{d}} / \Sigma_{k \neq j} m_k^j S_k^{\mathrm{d}}$ percent and country j's output rises by $m^j \alpha^{\mathrm{f}} m_i^j S_i^{\mathrm{d}} / \Sigma_{k \neq j} m_k^i S_k^{\mathrm{d}}$ percent, where m^j is country j's import share and m_i^j is the fraction of j's imports coming from country i. The last formula was used to compute the numbers in Table 5.

Table 5
Elasticities of total factor productivity with respect to R&D capital stocks in the G7 countries, 1990

	U.S.	Japan	Germany	France	Italy	U.K.	Canada
United States	...	0.0218	0.0039	0.0014	0.0005	0.0024	0.0024
Japan	0.0255	...	0.0008	0.0003	0.0001	0.0003	0.0001
West Germany	0.0465	0.0098	...	0.0081	0.0024	0.0060	0.0002
France	0.0369	0.0049	0.0156	...	0.0025	0.0049	0.0001
Italy	0.0254	0.0027	0.0166	0.0076	...	0.0032	0.0001
United Kingdom	0.0530	0.0069	0.0131	0.0047	0.0012	...	0.0003
Canada	0.0717	0.0019	0.0005	0.0002	0.0001	0.0005	...
Australia	0.0409	0.0092	0.0019	0.0005	0.0002	0.0018	0.0001
Austria	0.0301	0.0103	0.0611	0.0041	0.0033	0.0030	0.0001
Belgium	0.0930	0.0116	0.0812	0.0339	0.0039	0.0230	0.0004
Denmark	0.0449	0.0063	0.0250	0.0037	0.0012	0.0066	0.0001
Finland	0.0357	0.0103	0.0165	0.0027	0.0012	0.0053	0.0001
Greece	0.0290	0.0138	0.0287	0.0065	0.0057	0.0071	0.0001
Ireland	0.1032	0.0093	0.0095	0.0029	0.0008	0.0378	0.0001
Israel	0.1189	0.0045	0.0121	0.0030	0.0017	0.0083	0.0001
Netherlands	0.0832	0.0075	0.0430	0.0084	0.0016	0.0112	0.0002
New Zealand	0.0462	0.0130	0.0020	0.0005	0.0002	0.0036	0.0002
Norway	0.0643	0.0084	0.0185	0.0033	0.0012	0.0096	0.0006
Portugal	0.0542	0.0093	0.0294	0.0156	0.0049	0.0128	0.0003
Spain	0.0358	0.0047	0.0098	0.0060	0.0018	0.0037	0.0001
Sweden	0.0496	0.0092	0.0204	0.0036	0.0011	0.0070	0.0001
Switzerland	0.0453	0.0080	0.0400	0.0085	0.0032	0.0057	0.0001
Average elasticity of foreign total factor productivity	0.0422	0.0138	0.0091	0.0032	0.0010	0.0033	0.0011
Elasticity of domestic total factor productivity	0.2339	0.2339	0.2339	0.2339	0.2339	0.2339	0.2339
Average elasticity of total factor productivity in all 22 countries	0.1211	0.0446	0.0266	0.0180	0.0154	0.0179	0.0103

[a] Estimated elasticity of total factor productivity in the row country with respect to the R&D capital stock in the column country. Based on equation (iii) in Table 3. Averages are calculated using PPP-based GDP weights.

where α_{ij} stands for the elasticity of country i's output with respect to j's domestic R&D capital stock (the entries in Table 5), Y_i stands for country i's output, and S_j^d stands for country j's domestic R&D capital stock. This formula can be used to calculate all cross-country rates of return on R&D investment as well as the rates of return for groups of countries. Rather than report all these rates of return, we report the average rates of return for two groups of countries: the G7 and the remaining 15 smaller countries. These averages should be more accurate than the rates of return for individual countries because the coefficient α^d was estimated to be equal across countries within each group. [14]

Our calculations (based on the data in Tables 5 and A.7) show that in 1990 the average own rate of return from investment in R&D was 123 percent in the G7 countries and 85 percent in the remaining 15 countries. This means that a $100 increase in the R&D capital stock in a G7 country raises its GDP by $123 on average, and that a $100 increase in the R&D capital stock of one of the smaller 15 countries raises its GDP by $85 on average (based on PPP). In addition, in 1990 the average worldwide rate of return from investment in R&D in the G7 countries was 155 percent. These estimated rates of return are very high. For the G7 countries the difference between the worldwide and the own rate of return is about 30 percent, which implies a large international R&D spillover; about one quarter of the total benefits of R&D investment in a G7 country accrue to its trade partners.

Our estimated rates of return are sensitive to the calculated benchmarks for the R&D capital stocks, because they are sensitive to the levels of the R&D capital stocks. A proportional increase in the levels of R&D capital stocks will not affect the estimated coefficients in Table 3 (due to the presence of country dummies), but it will reduce our estimate of own rates of return on investment in R&D. For this reason we place more confidence in the estimated elasticities than in the estimated rates of return. Nevertheless, the estimated rates of return are indicative of the importance of R&D. Of course, our rates of return refer to the social or economy-wide rates of return from R&D, and thus include beneficial externalities that would not be reflected in the private rate of return from R&D investment by a specific enterprise.

Although the calculations of the international spillovers and the rates of return are based on equation (iii) in Table 3, they would be broadly similar if equations (i) and (ii) were used instead. [15] The specification of equation (iii) implies a linear relationship between the share of imports of goods or services and the benefits from foreign R&D that may not be realistic. For example, Japan has a very low ratio of imports to GDP, but is commonly thought to have benefited greatly from foreign R&D. We consider equation (iii) to be suggestive of the role that the level of trade may play in the international transmission of the benefits of R&D, which is likely to be a fruitful area for further empirical work.

[14] It follows from (3) that the own rate of return is given by $\rho_{jj} = \alpha_j^d Y_j / S_j^d$ and that the world wide rate of return on country j's R&D is given by $\rho_j = \Sigma_i \rho_{ij} = \alpha_j Y / S_j^d$, where $Y = \Sigma_i Y_i$ is aggregate GDP and $\alpha_j = \Sigma_i \alpha_{ij} Y_i / Y$ is the GDP weighted average elasticity of output with respect to country j's R&D capital stock. Now consider a set C of countries that have the same elasticity α. For this group of countries the average own rate of return equals $\rho_{CC} \equiv \Sigma_{j \in C} \rho_j S_j^d / (\Sigma_{i \in C} S_i^d)$.

[15] This is because the elasticities with respect to the domestic R&D capital stocks are of the same order of magnitude, as is the elasticity with respect to the foreign R&D capital stock (after the estimated coefficient in equation (iii) is divided by the average import share).

5. Closing comments

The emerging new theory of economic growth builds around innovation driven productivity developments. It draws its inspiration from historical studies that have shown the importance of inventive activities for long-run economic growth on the one hand and the role of economic incentives in propagating these activities on the other. This theory also underlines international economic relations, and in particular international trade, as transmission mechanisms that link a country's productivity gains to economic developments in its trade partners (see Grossman and Helpman (1994) for a review).

Although cross-country studies of economic growth have been recently in abundance, they typically focus on explaining output growth, as determined by the accumulation of labor, capital, and some additional economic and political variables. [16] The novelty of the new theory lies, however, in explaining the growth of total factor productivity, which is the component of output growth that is not attributable to the accumulation of inputs. For this reason we have chosen to follow the theory and focus on the central link between productivity and R&D.

Our evidence suggests that there indeed exist close links between productivity and R&D capital stocks. Not only does a country's total factor productivity depend on its own R&D capital stock, but as suggested by the theory, it also depends on the R&D capital stocks of its trade partners. While the beneficial effects on TFP from domestic R&D have been established in the earlier empirical literature, the evidence of the importance of foreign R&D is new. Foreign R&D may have a stronger effect on domestic productivity the more open an economy is to international trade. Some of our estimates of TFP with respect to R&D capital stocks suggest that in the large countries the elasticity is larger with respect to the domestic R&D capital stock than with respect to the foreign R&D capital stock, while in most of the smaller countries the elasticity is larger with respect to the foreign R&D capital stock. And our estimates suggest that the rate of return on

[16] Englander et al. (1988) and Helliwell (1992) also focus on total factor productivity. We report alternative estimates based on an output rather than on a total factor productivity specification in Appendix B.

R & D capital is very high, both in terms of domestic output and in terms of international spillovers.

These results are encouraging; they suggest that our search for international R & D spillovers was not misplaced. Further explorations with disaggregated data and an explicit treatment of R & D capital stock dynamics will undoubtedly provide valuable new insights.

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Appendix A: Data sources and definitions

For each country, total factor productivity F is defined as

$$F = Y / [K^{\beta} L^{(1-\beta)}],$$

where Y is value-added in the business sector, K is the stock of business sector capital, and L is employment in the business sector (except for the United States, Japan, and Israel, where L is total hours worked). All variables are constructed as indices with 1985 = 1. The coefficient β is the average share of capital income from 1987–89. Y, K, and L are from the OECD Analytical Data Base for all countries except Israel, and except for L for the United States, which is from the *Monthly Labor Review* (U.S. Department of Labor), and Japan, which is from the *Monthly Labor Survey* (Japan, Ministry of Labor). For Israel, Y is from the May 1991 Supplement to the *Monthly Bulletin of Statistics* (Israel, Central Bureau of Statistics) and estimates of K and L were provided by Rafi Melnick of the Bank of Israel. The estimates for total factor productivity are reported in Table A.1 and the capital shares are reported in Table A.2.

Table A.1
Total factor productivity (1985 = 1)

	U.S.	Japan	Germany	France	Italy	U.K.	Canada	Aus'lia	Austria	Belgium	Denmark	Finland	Greece	Ireland	Israel	Nether.	N.Z.	Norway	Portual	Spain	Sweden	Switz.
1971	0.950	0.712	0.873	0.807	0.771	0.823	0.888	0.885	0.891	0.805	0.846	0.784	0.867	0.825	0.858	0.836	1.030	0.691	0.889	0.899	0.909	0.973
1972	0.965	0.750	0.889	0.829	0.791	0.843	0.912	0.890	0.923	0.841	0.881	0.839	0.920	0.876	0.905	0.855	1.017	0.719	0.945	0.935	0.921	0.986
1973	0.978	0.789	0.913	0.855	0.835	0.887	0.943	0.915	0.942	0.878	0.894	0.871	0.956	0.888	0.922	0.886	1.062	0.745	1.040	0.957	0.950	1.000
1974	0.954	0.776	0.904	0.863	0.858	0.862	0.943	0.900	0.956	0.894	0.869	0.864	0.896	0.905	0.943	0.909	1.122	0.777	0.976	0.963	0.955	1.003
1975	0.952	0.790	0.900	0.854	0.817	0.852	0.940	0.899	0.945	0.874	0.871	0.859	0.937	0.919	0.952	0.897	1.035	0.790	0.879	0.942	0.952	0.960
1976	0.972	0.801	0.944	0.877	0.863	0.876	0.974	0.917	0.973	0.922	0.913	0.831	0.975	0.915	0.931	0.933	1.043	0.809	0.922	0.948	0.939	0.968
1977	0.984	0.823	0.956	0.892	0.879	0.891	0.983	0.904	0.991	0.918	0.911	0.834	0.987	0.958	0.920	0.946	1.007	0.818	0.960	0.955	0.909	0.983
1978	0.992	0.847	0.976	0.913	0.903	0.913	0.991	0.931	0.965	0.935	0.909	0.855	1.037	0.980	0.924	0.952	0.945	0.838	0.980	0.954	0.921	0.975
1979	0.981	0.878	0.997	0.936	0.946	0.925	0.986	0.948	0.990	0.940	0.926	0.902	1.050	0.964	0.920	0.955	0.947	0.873	1.023	0.938	0.948	0.986
1980	0.969	0.894	0.980	0.941	0.969	0.905	0.959	0.940	0.999	0.974	0.916	0.925	1.040	0.967	0.948	0.947	0.943	0.904	1.044	0.949	0.945	1.006
1981	0.976	0.907	0.966	0.946	0.966	0.914	0.956	0.951	0.974	0.968	0.912	0.924	0.986	0.988	0.976	0.941	0.972	0.889	1.040	0.946	0.940	0.995
1982	0.955	0.925	0.946	0.965	0.961	0.941	0.926	0.932	0.963	0.984	0.937	0.945	0.982	0.960	0.966	0.937	0.978	0.883	1.052	0.950	0.946	0.974
1983	0.972	0.936	0.964	0.967	0.963	0.977	0.943	0.935	0.981	0.988	0.956	0.963	0.967	0.947	0.963	0.960	0.998	0.926	0.994	0.961	0.959	0.979
1984	0.995	0.958	0.990	0.983	0.983	0.976	0.980	0.982	0.984	1.004	0.983	0.980	0.984	0.976	0.959	0.990	1.013	0.969	0.965	0.980	0.992	0.983
1985	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1986	1.011	1.014	0.999	1.020	1.015	1.035	1.002	0.983	0.991	1.004	1.006	1.025	1.006	0.974	1.037	0.999	0.994	1.001	1.039	1.008	1.023	1.012
1987	1.016	1.041	0.995	1.036	1.040	1.062	1.011	1.002	0.997	1.017	0.988	1.055	0.998	1.018	1.080	0.987	0.955	0.995	1.066	1.033	1.029	1.015
1988	1.032	1.091	1.017	1.070	1.067	1.072	1.019	0.999	1.027	1.048	0.984	1.108	1.024	1.035	1.095	0.997	0.984	0.992	1.084	1.051	1.033	1.028
1989	1.029	1.134	1.037	1.096	1.090	1.059	1.019	1.003	1.051	1.069	0.995	1.146	1.046	1.080	1.097	1.018	0.987	1.019	1.120	1.057	1.034	1.050
1990	1.022	1.185	1.058	1.108	1.083	1.055	1.007	0.988	1.075	1.088	1.011	1.133	1.038	1.110	1.139	1.031	0.978	1.046	1.143	1.061	1.017	1.059

Table A.2
Capital shares, R&D capital stock benchmarks, and PPP exchange rates

	Capital share β	R&D expenditure		R&D stock Benchmark	PPP exchange Rates–1985
		Available	Avg. growth		
United States	0.335	1963–90	2.50	590,423	...
Japan	0.312	1965–89	8.14	33,687	243.9
West Germany	0.401	1963–90	5.03	44,471	2.595
France	0.354	1970–90	3.46	61,555	7.489
Italy	0.376	1963–90	6.63	9,970	1343.8
U.K.	0.311	1969–89	1.18	116,101	0.587
Canada	0.368	1967–90	5.08	9,787	1.254
Australia	0.387	1976–88	9.66	3,632	1.151
Austria	0.358	1970–85	6.63	1,725	17.346
Belgium	0.355	1970–88	4.32	6,497	47.087
Denmark	0.338	1970–89	4.79	2,217	10.038
Finland	0.331	1969–89	8.05	1,012	6.080
Greece	0.290	1981–89	11.73	149	81.477
Ireland	0.281	1969–88	7.23	254	0.743
Israel	0.270	1971–89	10.65	335	764.8
Netherlands	0.390	1970–89	2.39	19,381	2.638
New Zealand	0.370	1972–89	4.06	495	1.354
Norway	0.285	1969–89	7.19	1,282	8.924
Portugal	0.328	1971–88	4.17	345	76.573
Spain	0.391	1969–89	10.40	1,007	112.5
Sweden	0.338	1969–89	5.96	5,491	8.373
Switzerland	0.211	1967–89	1.57	22,810	2.447

[a] Capital shares are 1987–89 averages. The average annual growth of R&D expenditures relates to the growth over the period for which estimates are available. The R&D capital stock benchmarks are in millions of U.S. dollars (based on PPP exchange rates) in 1985 prices and refer to one year before the first year after which the R&D expenditure estimates are available. PPP exchange rates are U.S. dollars per unit of local currency in 1985.

The estimates of business sector research and development capital stocks are based on R&D expenditure data from the OECD's *Main Science and Technology Indicators* except for Israel which is from the November 1990 Supplement to the *Monthly Bulletin of Statistics*. Real R&D expenditures are nominal expenditures deflated by an R&D price index (PR), which is defined as

$$PR = 0.5P + 0.5W,$$

where P is the implicit deflator for business sector output and W is an index of average business sector wages (the same source as for Y). This definition of PR implies that half of R&D expenditures are labor costs, which is broadly consistent with available data on the composition of R&D expenditures. For a number of smaller countries, R&D expenditure data are not available over the full 1970–90 period (see Table A.2), in which case an estimated equation relating real R&D

Table A.3
Domestic R&D capital stocks (in U.S. dollars, 1985 = 1)

	U.S.	Japan	Ger.	France	Italy	U.K.	Canada	Aus'lia	Austria	Belgium	Den.	Finland	Greece	Ireland	Israel	Nether.	N.Z.	Norway	Portugal	Spain	Sweden	Switz.
1971	0.632	0.346	0.486	0.656	0.493	0.864	0.523	0.358	0.360	0.539	0.582	0.336	0.094	0.405	0.264	0.794	0.590	0.377	0.667	0.234	0.394	0.876
1972	0.655	0.384	0.521	0.679	0.531	0.870	0.544	0.373	0.392	0.563	0.609	0.372	0.116	0.442	0.292	0.814	0.612	0.404	0.695	0.268	0.421	0.890
1973	0.678	0.424	0.555	0.704	0.570	0.875	0.564	0.395	0.431	0.591	0.636	0.410	0.144	0.477	0.324	0.834	0.637	0.434	0.724	0.306	0.449	0.902
1974	0.700	0.466	0.584	0.726	0.602	0.884	0.583	0.434	0.469	0.620	0.661	0.448	0.175	0.507	0.355	0.848	0.667	0.465	0.747	0.354	0.479	0.913
1975	0.720	0.507	0.612	0.748	0.633	0.894	0.604	0.473	0.505	0.652	0.683	0.484	0.203	0.536	0.388	0.866	0.701	0.497	0.759	0.412	0.513	0.922
1976	0.738	0.542	0.644	0.770	0.666	0.897	0.626	0.511	0.540	0.682	0.704	0.519	0.249	0.568	0.414	0.881	0.734	0.537	0.761	0.475	0.551	0.933
1977	0.811	0.577	0.673	0.792	0.694	0.905	0.644	0.559	0.581	0.714	0.728	0.553	0.303	0.599	0.453	0.897	0.755	0.577	0.758	0.538	0.589	0.941
1978	0.779	0.613	0.704	0.814	0.723	0.915	0.666	0.606	0.625	0.748	0.752	0.591	0.357	0.631	0.516	0.908	0.770	0.620	0.752	0.595	0.629	0.946
1979	0.801	0.649	0.742	0.835	0.749	0.927	0.691	0.653	0.675	0.781	0.778	0.634	0.424	0.669	0.572	0.919	0.793	0.662	0.745	0.646	0.670	0.954
1980	0.826	0.691	0.786	0.858	0.781	0.940	0.725	0.704	0.727	0.813	0.805	0.680	0.485	0.708	0.622	0.930	0.819	0.709	0.765	0.696	0.711	0.962
1981	0.853	0.740	0.828	0.883	0.815	0.953	0.766	0.758	0.781	0.845	0.835	0.733	0.548	0.759	0.667	0.943	0.854	0.755	0.798	0.755	0.757	0.969
1982	0.884	0.797	0.869	0.910	0.856	0.967	0.821	0.812	0.835	0.877	0.867	0.786	0.612	0.816	0.703	0.956	0.889	0.804	0.842	0.802	0.808	0.976
1983	0.918	0.857	0.911	0.939	0.900	0.979	0.880	0.863	0.889	0.914	0.905	0.849	0.720	0.873	0.755	0.968	0.919	0.860	0.890	0.867	0.866	0.981
1984	0.956	0.925	0.953	0.968	0.948	0.988	0.936	0.917	0.945	0.956	0.949	0.917	0.855	0.927	0.805	0.984	0.953	0.922	0.945	0.928	0.929	0.986
1985	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1986	1.050	1.087	1.050	1.035	1.065	1.013	1.079	1.110	1.056	1.046	1.056	1.092	1.148	1.089	1.076	1.025	1.052	1.095	1.058	1.095	1.079	1.020
1987	1.099	1.171	1.102	1.070	1.135	1.031	1.161	1.255	1.110	1.092	1.119	1.189	1.293	1.187	1.323	1.057	1.100	1.196	1.115	1.211	1.156	1.045
1988	1.146	1.259	1.155	1.108	1.208	1.050	1.241	1.404	1.166	1.139	1.187	1.291	1.448	1.290	1.550	1.092	1.146	1.297	1.176	1.332	1.232	1.068
1989	1.193	1.354	1.208	1.147	1.286	1.067	1.318	1.572	1.228	1.187	1.258	1.402	1.603	1.393	1.740	1.127	1.196	1.396	1.241	1.485	1.302	1.092
1990	1.237	1.462	1.264	1.189	1.372	1.080	1.391	1.755	1.300	1.244	1.329	1.520	1.757	1.501	1.933	1.161	1.246	1.495	1.315	1.648	1.362	1.113

Table A.4
Bilateral import shares (percent of total imports from countries listed, 1990)

	U.S.	Japan	Ger.	France	Italy	U.K.	Canada	Aus'lia	Austria	Belgium	Den.	Finland	Greece	Ireland	Israel	Nether.	N.Z.	Norway	Portugal	Spain	Sweden	Switz.
United States		45.77	9.43	9.55	7.23	13.26	75.93	29.76	4.30	5.27	8.01	8.04	4.24	17.28	21.37	10.10	20.25	9.27	5.39	11.85	9.35	7.10
Japan	32.47		7.94	5.12	3.06	6.90	8.21	26.74	5.87	2.64	4.50	9.32	8.10	6.28	3.23	3.64	22.94	4.85	3.73	6.27	6.96	5.05
Germany	8.58	8.49		24.06	28.12	19.46	3.19	8.32	51.76	27.34	26.48	22.06	24.95	9.42	12.95	31.01	5.24	15.86	17.37	19.30	22.84	37.28
France	4.52	5.24	14.92		19.51	10.54	1.74	3.24	5.23	17.36	5.89	5.39	8.52	4.41	4.85	9.20	1.87	4.26	14.04	17.90	6.08	12.08
Italy	4.26	3.59	11.15	14.29		6.52	1.73	4.00	10.64	4.94	4.69	5.93	18.69	2.84	6.95	4.40	2.29	3.77	10.97	13.66	4.71	11.29
UK	6.31	4.21	8.56	8.88	6.43		3.93	8.95	2.98	9.16	8.30	8.36	7.27	44.55	10.49	9.59	11.01	9.68	8.96	8.51	9.22	6.24
Canada	29.94	8.16	1.07	0.90	1.00	2.22		3.15	0.56	0.77	0.62	1.11	0.59	0.83	0.81	0.92	2.45	2.82	1.02	0.63	0.93	0.46
Australia	1.40	10.91	0.59	0.64	0.84	0.84	0.07		0.08	0.48	0.35	0.46	0.13	0.14	0.43	0.39	25.91	0.43	0.38	0.45	0.50	0.14
Austria	0.40	0.49	5.17	1.05	3.06	0.91	0.32	0.48		0.92	1.44	1.57	1.74	0.37	0.54	1.05	0.41	1.28	0.92	1.08	1.57	4.28
Belgium	1.59	1.38	8.62	11.41	6.57	5.54	0.49	1.10	3.19		3.84	3.55	4.81	2.34	18.22	17.08	0.86	3.33	4.76	4.14	3.58	3.84
Denmark	0.54	1.13	2.28	1.03	1.25	2.17	0.22	0.58	0.83	0.68		3.97	1.60	1.00	0.52	1.38	0.53	8.66	1.12	0.99	7.84	1.09
Finland	0.49	0.50	1.28	0.91	0.66	1.84	0.32	0.88	0.95	0.52	3.45		1.16	0.90	0.72	1.22	0.41	3.92	0.76	0.87	7.69	0.73
Greece	0.18	0.17	0.84	0.51	1.53	0.38	0.06	0.22	0.51	0.22	0.34	0.36		0.12	0.37	0.25	0.14	1.37	0.21	0.32	0.32	0.16
Ireland	0.54	0.62	1.08	1.08	0.86	4.16	0.14	0.46	0.45	0.82	0.76	0.61	0.72		0.32	1.12	0.30	1.24	0.41	0.90	0.73	0.63
Israel	1.11	0.72	0.34	0.35	0.38	0.47	0.13	0.39	0.18	0.76	0.16	0.20	0.53	0.21		0.42	0.23	0.22	0.15	0.34	0.16	0.45
Netherland	1.70	1.06	12.82	6.44	7.29	9.35	0.71	1.40	3.26	20.45	6.81	4.09	9.07	4.46	4.16		1.43	4.32	6.59	4.29	4.79	4.51
New Zealand	0.45	1.56	0.12	0.14	0.17	0.42	0.19	5.34	0.06	0.30	0.11	0.06	0.28	0.14	0.00	0.06		0.05	0.08	0.16	0.06	0.05
Norway	0.71	0.53	1.80	1.76	0.52	3.53	0.68	0.56	0.46	0.95	5.20	2.96	0.51	0.41	0.26	1.62	0.33		1.08	0.68	7.96	0.68
Portugal	0.28	0.16	0.99	1.28	0.51	1.01	0.14	0.16	0.67	0.45	1.19	1.07	0.48	0.50	0.31	0.72	0.15	1.54		3.05	1.36	0.41
Spain	1.20	0.65	2.62	5.48	3.22	2.81	0.49	0.59	1.01	1.65	1.24	1.36	2.36	1.35	1.28	1.58	0.42	1.43	17.67		1.24	1.28
Sweden	1.72	1.02	3.16	2.06	2.02	3.64	0.81	2.30	2.11	2.46	14.28	17.32	2.12	1.74	1.11	2.66	1.66	19.80	1.89	2.58		2.22
Switzerland	1.61	3.64	5.24	3.05	5.74	4.02	0.52	1.38	4.91	1.89	2.35	2.21	2.12	0.69	11.09	1.59	1.17	1.90	2.50	2.04	2.12	
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Table A.5
Foreign R & D capital stock (in U.S. dollars, weighted by import shares, 1985 = 1)

	U.S.	Japan	Ger.	France	Italy	U.K.	Canada	Aus'lia	Austria	Belgium	Den.	Finland	Greece	Ireland	Israel	Nether.	N.Z.	Norway	Portugal	Spain	Sweden	Switz.
1971	0.423	0.683	0.788	0.686	0.789	0.670	0.614	0.637	0.554	0.742	0.723	0.596	0.702	0.519	0.633	0.593	0.576	0.550	0.426	0.719	0.647	0.646
1972	0.457	0.647	0.776	0.647	0.762	0.611	0.630	0.599	0.594	0.664	0.792	0.577	0.744	0.565	0.669	0.614	0.522	0.529	0.437	0.670	0.644	0.619
1973	0.485	0.656	0.699	0.654	0.747	0.608	0.644	0.606	0.594	0.656	0.743	0.573	0.769	0.551	0.597	0.584	0.544	0.544	0.507	0.686	0.622	0.633
1974	0.504	0.667	0.731	0.685	0.772	0.627	0.683	0.651	0.600	0.683	0.745	0.597	0.927	0.536	0.627	0.631	0.568	0.588	0.483	0.713	0.613	0.633
1975	0.526	0.721	0.754	0.732	0.820	0.657	0.704	0.660	0.619	0.746	0.755	0.657	1.048	0.537	0.665	0.680	0.635	0.691	0.552	0.783	0.631	0.668
1976	0.545	0.732	0.759	0.728	0.889	0.667	0.733	0.670	0.643	0.753	0.765	0.706	0.939	0.575	0.828	0.744	0.695	0.657	0.679	0.831	0.656	0.735
1977	0.583	0.700	0.799	0.737	0.862	0.705	0.760	0.697	0.675	0.771	0.742	0.704	0.960	0.615	0.794	0.744	0.723	0.652	0.573	0.819	0.695	0.738
1978	0.627	0.718	0.748	0.742	0.843	0.740	0.784	0.728	0.697	0.798	0.800	0.723	0.885	0.641	0.735	0.746	0.721	0.675	0.633	0.781	0.742	0.763
1979	0.682	0.737	0.783	0.768	0.848	0.739	0.799	0.785	0.732	0.812	0.815	0.766	0.933	0.640	0.714	0.761	0.752	0.701	0.684	0.845	0.770	0.825
1980	0.711	0.801	0.807	0.817	0.877	0.755	0.839	0.829	0.778	0.873	0.826	0.805	0.966	0.655	0.821	0.793	0.767	0.749	0.724	0.826	0.798	0.826
1981	0.765	0.867	0.894	0.897	0.927	0.881	0.864	0.859	0.832	0.973	0.928	0.927	1.006	0.685	0.878	0.844	0.845	0.833	0.739	0.949	0.841	0.858
1982	0.832	0.892	0.945	0.954	0.976	0.888	0.888	0.930	0.922	0.974	1.126	1.096	1.049	0.774	0.945	0.918	1.007	0.925	0.810	1.045	0.913	0.917
1983	0.884	0.940	0.955	0.958	1.003	0.916	0.920	0.938	0.937	1.002	1.038	1.010	1.036	0.827	0.915	0.926	0.965	0.959	0.787	1.046	0.960	0.945
1984	0.929	0.976	0.943	0.965	0.964	0.936	0.963	0.962	0.947	0.984	0.971	1.018	1.007	0.910	0.926	0.958	0.969	0.971	0.960	0.990	0.990	1.044
1985	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1986	1.115	1.045	1.026	1.020	1.029	1.036	1.035	1.038	1.070	1.012	1.109	1.072	1.062	1.055	0.990	1.000	1.092	0.941	0.846	0.996	1.074	1.000
1987	1.247	1.065	1.018	1.033	0.998	0.995	1.058	1.071	1.080	1.018	1.125	1.027	1.052	1.056	0.912	0.981	1.200	0.958	0.667	0.859	1.063	1.022
1988	1.326	1.053	1.042	1.050	1.005	1.033	1.097	1.118	1.139	1.048	1.160	1.123	1.046	1.146	0.870	0.980	1.142	0.942	0.586	0.795	1.061	1.069
1989	1.376	1.094	1.130	1.145	1.063	1.097	1.123	1.170	1.199	1.038	1.258	1.251	1.163	1.154	0.895	1.044	1.238	1.004	0.564	0.840	1.156	1.131
1990	1.444	1.146	1.268	1.187	1.094	1.220	1.175	1.270	1.268	1.108	1.384	1.292	1.178	1.195	0.991	1.140	1.299	1.125	0.585	0.874	1.220	1.230

Table A.6
Imports as a share of GDP (ratio)

	U.S.	Japan	Ger.	France	Italy	U.K.	Canada	Aus'lia	Austria	Belgium	Den.	Finland	Greece	Ireland	Israel	Nether.	N.Z.	Norway	Portugal	Spain	Sweden	Switz.
1970	0.0552	0.0958	0.1914	0.1528	0.1560	0.2145	0.2001	0.1475	0.3081	0.4387	0.3090	0.2678	0.1700	0.4212	0.5002	0.4513	0.2548	0.4535	0.3359	0.1466	0.2282	0.3907
1971	0.0568	0.0907	0.1897	0.1534	0.1547	0.2106	0.2008	0.1422	0.2969	0.4362	0.2944	0.2591	0.1675	0.4018	0.4984	0.4469	0.2159	0.4500	0.3283	0.1372	0.2108	0.3597
1972	0.0615	0.0835	0.1860	0.1568	0.1628	0.2126	0.2097	0.1217	0.2875	0.4215	0.2650	0.2440	0.1578	0.3776	0.4487	0.4109	0.2112	0.4066	0.3100	0.1477	0.2037	0.3400
1973	0.0676	0.1006	0.1891	0.1670	0.1873	0.2552	0.2200	0.1272	0.3071	0.4773	0.3043	0.2576	0.1752	0.4236	0.5781	0.4303	0.2491	0.4521	0.3500	0.1566	0.2184	0.3441
1974	0.0874	0.1446	0.2197	0.2170	0.2379	0.3238	0.2456	0.1689	0.3436	0.5638	0.3468	0.3252	0.2167	0.5448	0.5517	0.5005	0.3532	0.5133	0.4212	0.1983	0.3067	0.3829
1975	0.0774	0.1286	0.2177	0.1787	0.2010	0.2721	0.2411	0.1430	0.3032	0.4895	0.3102	0.2973	0.1819	0.4345	0.5518	0.4613	0.2932	0.5000	0.3580	0.1775	0.2719	0.2827
1976	0.0855	0.1275	0.2342	0.2031	0.2279	0.2924	0.2288	0.1484	0.3413	0.5036	0.3349	0.2633	0.1868	0.4842	0.5268	0.4672	0.3231	0.5216	0.3642	0.1859	0.2790	0.3029
1977	0.0924	0.1142	0.2309	0.2036	0.2170	0.2902	0.2352	0.1626	0.3497	0.5534	0.3246	0.2512	0.2030	0.5609	0.5020	0.4528	0.2866	0.5171	0.3825	0.1653	0.2699	0.3408
1978	0.0951	0.0938	0.2227	0.1908	0.2069	0.2692	0.2486	0.1632	0.3329	0.5452	0.2995	0.2469	0.1962	0.5282	0.5338	0.4437	0.2612	0.4196	0.3647	0.1439	0.2513	0.3265
1979	0.1015	0.1247	0.2441	0.2064	0.2267	0.2742	0.2654	0.1664	0.3610	0.6137	0.3207	0.2979	0.2137	0.6112	0.5251	0.4962	0.2934	0.4229	0.3988	0.1472	0.2943	0.3585
1980	0.1085	0.1459	0.2690	0.2275	0.2411	0.2485	0.2644	0.1775	0.3877	0.6679	0.3376	0.3460	0.2328	0.5638	0.4768	0.5305	0.3178	0.4266	0.4123	0.1814	0.2988	0.4028
1981	0.1048	0.1393	0.2794	0.2353	0.2483	0.2370	0.2612	0.1787	0.3963	0.7726	0.3581	0.3208	0.2487	0.5646	0.5018	0.5448	0.3169	0.3996	0.4485	0.2018	0.2844	0.3838
1982	0.0963	0.1380	0.2747	0.2370	0.2357	0.2430	0.2206	0.1817	0.3639	0.8214	0.3594	0.3002	0.2625	0.5432	0.5177	0.5336	0.3304	0.4097	0.4476	0.2057	0.3135	0.3503
1983	0.0964	0.1216	0.2674	0.2265	0.2099	0.2548	0.2214	0.1599	0.3612	0.8089	0.3437	0.2982	0.2614	0.5415	0.5374	0.5386	0.3328	0.3851	0.4290	0.2186	0.3355	0.3524
1984	0.1072	0.1227	0.2816	0.2350	0.2253	0.2844	0.2488	0.1720	0.3883	0.8641	0.3545	0.2782	0.2993	0.5865	0.5205	0.5690	0.3241	0.3820	0.4451	0.2136	0.3282	0.3806
1985	0.1034	0.1109	0.2901	0.2325	0.2267	0.2767	0.2581	0.1912	0.4055	0.8552	0.3633	0.2833	0.3278	0.5761	0.4985	0.5871	0.3679	0.3890	0.4085	0.2119	0.3363	0.3863
1986	0.1058	0.0741	0.2496	0.2016	0.1818	0.2626	0.2637	0.1868	0.3602	0.7563	0.3249	0.2514	0.3089	0.5159	0.5280	0.4970	0.3491	0.4147	0.3551	0.1773	0.2974	0.3550
1987	0.1117	0.0723	0.2395	0.2051	0.1825	0.2642	0.2547	0.1762	0.3518	0.7463	0.2961	0.2497	0.3200	0.5121	0.5930	0.4959	0.3200	0.3766	0.4086	0.1922	0.3076	0.3472
1988	0.1127	0.0783	0.2434	0.2123	0.1830	0.2648	0.2581	0.1754	0.3694	0.7902	0.2935	0.2488	0.3044	0.5278	0.5654	0.5041	0.2805	0.3740	0.4574	0.1997	0.3074	0.3606
1989	0.1119	0.0928	0.2613	0.2278	0.1960	0.2769	0.2548	0.1864	0.3886	0.8819	0.3114	0.2536	0.3202	0.5610	0.5196	0.5385	0.2261	0.3767	0.4487	0.2137	0.3162	0.3826
1990	0.1133	0.1010	0.2538	0.2265	0.1950	0.2684	0.2559	0.1759	0.3914	0.8970	0.2996	0.2407	0.3260	0.5331	0.5371	0.5157	0.3035	0.3683	0.4516	0.2047	0.3004	0.3635

Table A.7
GDP and domestic R&D capital stock, 1990 [a]

	GDP	S^d	GDP/S^d	Average ratio
United States	4568.5	1041.8	4.39	
Japan	1551.1	259.6	5.97	
West Germany	865.9	175.3	4.94	
France	712.3	115.4	6.17	5.24
Italy	688.3	46.4	14.83	
United Kingdom	702.1	148.2	4.74	
Canada	439.8	31.2	14.10	
Australia	228.4	9.1	25.10	
Austria	86.6	6.6	13.12	
Belgium	116.7	15.7	7.43	
Denmark	63.7	5.3	12.02	
Finland	64.9	5.5	11.80	
Greece	61.2	0.5	122.40	
Ireland	24.2	1.1	22.00	10.91
Israel	45.0	2.5	18.00	
Netherlands	174.2	29.0	6.01	
New Zealand	34.2	1.0	34.20	
Norway	60.4	5.9	10.24	
Portugal	55.3	0.7	79.00	
Spain	298.7	8.7	34.33	
Sweden	113.6	21.5	5.28	
Switzerland	145.3	31.0	4.69	

[a] GDP and R&D capital stocks are in 1985 U.S. dollars, based on PPP.

expenditures to real output and investment (all in logarithms) was used to 'predict' the missing R&D expenditure data.

Research and development capital stocks (S), which are defined here as beginning of period stocks, were calculated from R&D expenditure (R) based on the perpetual inventory model

$$S_t = (1-\delta)S_{t-1} + R_{t-1},$$

where δ is the depreciation or obsolescence rate, which was assumed to be 5 percent. [17] The benchmark for S was calculated following the procedure suggested by Griliches (1980), as

$$S_0 = R_0/(g+\delta),$$

[17] Alternative measures of the R&D capital stocks were also calculated assuming $\delta = 0$, $\delta = 0.1$, and $\delta = 0.15$. Regressions comparable to those reported in Table 3 but using alternative R&D capital stocks assuming $\delta = 0.15$ are reported in Appendix B.

where g is the average annual logarithmic growth of R & D expenditures over the period for which published R & D data were available, R_0 is the first year for which the data were available, and S_0 is the benchmark for the beginning of the year. The domestic R & D capital stocks were converted into U.S. dollars using 1985 purchasing power parity exchange rates from Gulde and Schulze-Ghattas (1992). The calculated benchmarks and PPP exchange rates are reported in Table A.2, and the estimates of the domestic R & D capital stocks are reported in Table A.3.

For each of the 22 countries, two measures of the foreign R & D capital stock were constructed. The first is simply the sum of the domestic R & D capital stocks of each countries' 21 trading partners. The second estimate of the foreign R & D capital stock is a bilateral import-share weighted average of the domestic R & D capital stocks of each countries' 21 trading partners. The bilateral import shares were calculated for each year from 1970–90 based on data from the IMF's *Direction of Trade*. The bilateral import-share weighting matrix for 1990 is reported in Table A.4, and estimates of the import-share weighted foreign R & D capital stocks are reported in Table A.5. We do not report foreign R & D capital stocks based on simple sums because they are not used in the main text. Experimental estimation using these foreign R & D capital stocks indicated that the import weighted stocks are preferable. Since the latter are also preferable on theoretical grounds we have chosen to concentrate on them.

The ratios of the imports of goods and services to GDP, which are from the IMF's World Economic Outlook database, are reported in Table A.6. The data used to calculate the rates of return to R & D capital are reported in Table A.7.

Appendix B: Additional estimation results

As noted above, the R & D capital stocks used in the text are based on an assumed depreciation or obsolescence rate of 5 percent. Private rates of depreciation for R & D expenditures are typically estimated to be considerably higher, in part because of the loss of quasi-rents as the knowledge generated by R & D becomes widely known. A number of studies have assumed depreciation rates of 15 percent (Griliches, 1990). Table B.1 reports estimation results comparable to those in Table 3 except that the R & D capital stocks have been constructed assuming a 15 percent depreciation rate. In general, the estimation results are similar to those in Table 3. The main differences are that the elasticity of TFP with respect to the domestic R & D capital stock is increased (although it is reduced somewhat for the G7 countries in equations (ii) and (iii)), while the elasticity with respect to the foreign R & D capital stock is reduced.

Table B.1 also reports estimation results that allow coefficients to change over time based on the specification of equation (iii) in Table 3. Including dummy variables for each year from 1971 to 1989, as is done in equation (iv), reduces the sizes of the estimated coefficients. Some empirical studies have suggested that the beneficial effects of R & D on output or total factor productivity may have changed over time (Griliches, 1988, 1990). To test this, equation (v) includes each of the R & D capital stock variables multiplied by a time trend (T). From 1971 ($T = 1$) to 1990 ($T = 20$), the estimated elasticity on the domestic R & D capital stock increases from 0.046 (0.041 + 0.005) to 0.141 for the smaller countries, while it decreases from 0.179 to 0.103 for the G7 countries. The estimated elasticity on foreign R & D falls from 0.488 in 1971 to about 0 in 1986; thereafter it is negative and falls to −0.112 in 1990. This specification implies steady changes in all of the estimated elasticities over the full sample period. Equation (vi) tests for a discrete shift in the estimated coefficients in 1981 by including each of the R & D stock variables multiplied by a dummy variable ($D8$) that is 0 from 1971–80 and 1 from 1981–90. The implications of equations (v) and (vi) are similar: the estimated elasticity of the domestic R & D capital stock increases in the 1980s for the smaller

Table B.1
Estimation results assuming a 15 percent depreciation rate for R&D capital and allowing coefficients to change over time (Pooled data 1971–90 for 22 countries, 440 observations) [a]

	15% depreciation rate			5% depreciation rate		
	(i)	(ii)	(iii)	(iv)	(v)	(vi)
$\log S^d$	0.140	0.123	0.109	0.032	0.041	0.060
$G7 \cdot \log S^d$		0.124	0.138	0.110	0.183	0.162
$\log S^f$	0.048	0.033				
$m \cdot \log S^f$			0.197	0.122	0.520	0.363
$\log S^d \cdot \rightarrow$					T 0.005	$D8$ 0.090
$G7 \cdot \log S^d \cdot \rightarrow$					T −0.004	$D8$ −0.021
$m \cdot \log S^f \cdot \rightarrow$					T −0.032	$D8$ −0.313
Standard error	0.048	0.045	0.045	0.042	0.043	0.043
R^2	0.578	0.629	0.642	0.700	0.676	0.674
R^2 adjusted	0.555	0.608	0.621	0.668	0.654	0.652
Cointegration tests:						
Levin and Lin (1992)	−5.989	−9.677	−6.371	−5.575	−5.061	−5.525
Levin and Lin (1993)	0.266	2.036	1.756	1.578	2.536	2.666
t-statistic on the lagged residual in the EC model	−6.286	−7.133	−7.725	−5.787	−7.137	−7.493

[a] Equations (i)–(iii) are the same as in Table 3 except that the R&D capital stocks have been constructed using a 15 (rather than 5) percent depreciation rate. Equations (iv)–(vi) are specified the same as equation (iii) in Table 3 except that equation (iv) includes unreported, year-specific dummies for each year from 1971–89; equation (v) allows each of the coefficients to vary over time according to a time trend; and equation (vi) allows each coefficient to shift in 1981–90 compared with 1971–80. The dependent variable is log (total factor productivity). All equations include unreported, country-specific constants. See notes to Table 3. T = time trend equal to 1 in 1971, 2 in 1972, etc.; $D8$ = dummy variable equal to 0 from 1971–80 and equal to 1.0 from 1981–90.

Table B.2
Production function estimation results (pooled data 1971–90 for 22 countries, 440 observations) [a]

	(i)	(ii)	(iii)	(iv)
$\beta \log K$	1.366	1.147	1.336	1.026
$(1-\beta)\log L$	0.868	0.752	0.911	0.784
$\log S^d$	0.052	0.075	0.049	0.079
$G7 \cdot \log S^d$		0.096		0.128
$\log S^f$	0.037	0.054		
$m \cdot \log S^f$			0.188	0.303
Standard error	0.045	0.044	0.045	0.042
R^2	0.921	0.926	0.923	0.932
R^2 adjusted	0.916	0.922	0.919	0.927
Cointegration tests:				
Levin and Lin (1992)	−5.793	−5.690	−6.089	−6.292
Levin and Lin (1993)	−2.027	0.335	−1.828	−0.215
t-statistic on the lagged residual in the EC model	−6.425	−7.461	−6.902	−8.455
Memoranda:				
Average coefficient on				
$\log K$	0.458	0.384	0.448	0.344
$\log L$	0.577	0.500	0.606	0.521
Sum	1.035	0.884	1.054	0.865

[a] The dependent variable is log output. All equations include unreported, country-specific constants. See notes to Table 3. K = capital stock; L = employment; β = average share of capital in each country over the period 1987–89; the average across all countries is 0.335.

countries and declines somewhat for the G7 countries, while the elasticity of foreign R&D decreases in the 1980s, although it does not become negative.

We report in Table B.2 regressions similar to those in Table 3 except that they are specified as a production function. The coefficients on capital and labor are allowed to vary according to the factor shares in each country; this is done by multiplying capital and labor in each country by its respective factor share (β). The evidence for cointegration is strongest in equations (i) and (iii), which do not allow the estimated coefficients on the domestic R&D stock to differ between the small and the large economies: both of these equations pass the Levin and Lin (1993) and the t-test for cointegration, and come close to passing the Levin and Lin (1992) test. The sum of the implied coefficients on physical capital and labor are remarkably close to unity, particularly in equations (i) and (iii), indicating constant returns to scale to physical capital and labor (cf. the memoranda to Table B.2). The implied coefficients on capital are somewhat larger than suggested by factor shares, while the opposite is true for the coefficients on labor. The estimated elasticities of output with respect to the R&D capital stocks are somewhat lower than reported in Table 3, but are comparable to results from single-country studies.

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