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INTERNATIONAL R&D SPILLOVERS

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ABSTRACT

Investment in research and development (R&D) affects a country's total factor productivity. Recently new theories of economic growth have emphasized this link and have also identified a number of channels through which a country's R&D affects total factor productivity of its trade partners. Following these theoretical developments we estimate the effects of a country's R&D capital stock and the R&D capital stocks of its trade partners on the country's total factor productivity. We find large effects of both domestic and foreign R&D capital stocks on total factor productivity. The foreign R&D capital stocks have particularly large effects on the smaller countries in our sample (that consists of 22 countries). Moreover, we find that about one quarter of the worldwide benefits of investment in R&D in the seven largest economies are appropriated by their trade partners.

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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 technical progress. The 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] and 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] and 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 levels. We explain the rational 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 1970–1990. 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. 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 we find that the foreign R&D capital stock is 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 is more important.

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 the 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.[1] In the simplest case a closed economy manufactures final output Y from an assortment of intermediate inputs $x(j)$, $j \in [0,n]$, where n is a measure of available intermediate inputs. The production function can be written in the form:

$$(1) \qquad Y = D(\cdot),$$

where D is a linear homogeneous function of the employed inputs, given n.

Two stories appear to be common in the formulation of D. In one case the inputs are horizontally differentiated. A simple formalization of this view takes D 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. Then all inputs are equally priced and equally employed in

[1] The reader is referred to Helpman (1992) for a review and to Grossman and Helpman (1991, Chaps. 3 and 4) for a detailed discussion of the two basic models that are used below.

production. The result is that

(2) $$D = n^{\frac{1}{\sigma-1}} X ,$$

where σ is the elasticity of substitution and $X = nx$ represents aggregate employment of intermediates.

Aggregate use of intermediates X is proportional to the labor force employed in manufacturing. 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 n is a function of the country's cumulative R&D effort.[2] 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, X/L. 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 indeed in our sample),[3] the ratio X/L is very close to one and it remains approximately constant. In this event 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 input j in manufacturing depends on the number of times it has been improved. Inputs that have

[2]The flow of new products equals $\dot{n}$ per unit time. Let this flow be proportional to real spending on R&D per unit time; say $\dot{n} = ar$, where a is a constant and r represents real spending on R&D. Then $n(T) \equiv \int_{-\infty}^{T} \dot{n}(t)dt = a\int_{-\infty}^{T} r(t)dt$. Namely, n is proportional to cumulative R&D spending.

[3] In the OECD countries in the 1980s, R&D expenditures averaged about 1.5 percent of GDP with a maximum of about 2 percent.

been improved more times are more productive. Input j that has been improved m times is λ times more productive than the same input that has been improved only $m-1$ times ($\lambda > 1$). Now let D be a Cobb–Douglas function with equal coefficients on all inputs. The measure of available inputs is taken to be constant, and we choose for simplicity $n = 1$. As in the previous case, we assume that a unit of labor produces a unit of $x(j)$. This production technology applies to all inputs and all quality levels. In this event only the highest quality inputs survive market competition. They are equally priced and employed in equal quantities in production. Under these circumstances

(3) $$D = \lambda^{I} X ,$$

where X represents again the volume of employed inputs. Here I depends on cumulative R&D as follows. Suppose that at time $t = 0$ the quality of all inputs equals one. R&D that is targeted at improving input j generates a probability of success that is proportional to the R&D effort. The target is always the highest quality of j. If under these circumstances all products are targeted with equal intensity at a point in time t (as they will be in equilibrium) and we denote with $\iota(t)$ the instantaneous fraction of inputs that are improved per unit time, then $\iota(t)$ is proportional to the instantaneous R&D effort per product. This means that in a time interval of length dt innovators improve a fraction $\iota(t)dt$ of inputs. Given the Cobb–Douglas structure of the production function, this specification implies that at time T the average quality of inputs equals $\lambda^{I(T)}$, where $I(T) = \int_0^T \iota(t)dt$. Since $\iota(t)$ is proportional to the R&D effort at time t, it follows that $I(T)$ depends on the cumulative R&D effort.

It is now straightforward to argue, as we did in the case of horizontally differentiated inputs, that total factor productivity depends on cumulative R&D and the share of labor absorbed in manufacturing. Relying again on the fact that in the data there is little variation in the share of R&D in GDP, we expect differences in cumulative R&D to explain most of the variation in TFP.

Two aspects of these examples require further elaborations. First, we have disregarded capital accumulation. Second, we have disregarded international trade.

In order to see how capital accumulation changes the basic relationship between TFP and cumulative R&D we now consider a simplified version of an extension proposed by Grossman and Helpman (1991, Chap. 5).[4] Let now the production function of final output Y be of the form

$$(4) \qquad Y = K^{\beta}D^{1-\beta},$$

where K is the stock of capital and D depends on intermediate inputs in one of the two forms that we discussed above, and β is a parameter between zero and one. As before, intermediates are manufactured from labor with one unit of input per unit output. In this case we measure logTFP by $\log Y - \beta \log K - (1-\beta)\log L$. It follows that logTFP equals $(1-\beta)\log(D/L)$. As before, D is given by (2) in the case of horizontally differentiated intermediate inputs and by (3) in the case of vertically differentiated intermediate inputs. Therefore in either case variations in TFP should be predominantly explained by variations in cumulative R&D, following the same arguments that we brought to bear on this issue in the simpler models with production that does not require capital. In fact, the previous models are a special case with $\beta = 0$. We conclude that the possibility of capital accumulation does not affect the result that differences in cumulative R&D should explain differences in total factor productivity.

Next consider international trade. The previous arguments apply in the absence of international trade in intermediate inputs, regardless of whether final output is traded

[4]Their model also allows for direct labor use in the manufacturing of Y. This possibility does not change our conclusions, however.

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 $j \in [0,n]$ are traded internationally, all of them are equally priced, and final output is not traded. Under these circumstances the above derived equations remain valid, except that now we need to interpret n as the measure of inputs that are manufactured in the world economy rather than in any particular country, and we need to interpret λ^{I} as the average quality of inputs in the world economy rather than in any particular country. It follows that with internationally traded intermediate inputs, n depends on cumulative R&D in the world economy and so does I. Therefore in this case variations in a country's TFP are mostly attributable to variations in the *world's* R&D capital stock. In particular, it follows that in this case domestic R&D has the same productivity effect 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:

$$(5) \qquad \log F_i = \alpha_i^{o} + \alpha_i^{d}\log S_i^{d} + \alpha_i^{f}\log S_i^{f},$$

where i is a country index, logF is the log of total factor productivity [equal to logY –

βlogK – (1–β)logL], S^d represents the domestic R&D capital stock and S^f the foreign R&D capital stock.[5] 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.[6] The specification of (5) 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 $\alpha^f = 0$.

The specification of (5) does not capture adequately the role of international trade. True, the foreign stock of knowledge S^f consists of import weighted foreign R&D capital stocks. But these weights are fractions that add up to one and therefore do not properly reflect the *level* of imports. We expect 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 should experience a larger TFP benefit 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 (5) that accounts for the interaction between foreign R&D capital stocks and the level of international trade seems preferable. To this end we estimate

$$\text{(6)} \qquad \log F_i = \alpha_i^0 + \alpha_i^d \log S_i^d + \alpha_i^f m_i \log S_i^f ,$$

[5] TFP refers to the flow of output during the period per unit of combined inputs, whereas both R&D capital stocks refer to the beginning of the period.

[6] We always allow the constants α^0 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. Second, even if this were not the case, the construction of the variables in the appendix in the form of index numbers, and the fact that TFP is measured in domestic currency whereas both R&D capital stocks are in U.S. dollars, implies that for comparability reasons we need to allow different constants across countries.

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 $\alpha^f m$. It follows that whenever α^f is the same for all countries the latter elasticity varies across countries in proportion to their import shares.[7]

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. As shown in Table 1, over the 1970–1990 period total factor productivity increased over time in all countries except for New Zealand and Sweden. But the upward trend was neither uniform across countries nor uniform over time. Japan and Norway experienced the fastest rate of productivity growth (with 68.3% and 56.6%, respectively) while in New Zealand productivity declined by 5.1% and in Sweden by 14.1%. Other countries had intermediate values. In the US, for example, TFP increased by about 9.7%, in Canada by 17.0%, in Belgium by 37.7%, in the Netherlands by 26.0%, and in Switzerland by 6.3%. Figure 1 provides plots of TFP for six of these countries; they clearly exhibit substantial fluctuations.

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. In Israel and Spain this stock was seven fold larger by the end of the period than at the beginning, and it had more than quadrupled in Japan, Australia, Finland

[7] 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

	TFP growth (1970-90) in %	S^d_{1990}/S^d_{1971}	S^f_{1990}/S^f_{1971}	m in % 1971	m in % 1990
United States	9.7	2.0	3.4	5.5	11.2
Japan	68.3	4.2	1.7	9.6	9.3
West Germany	22.6	2.6	1.6	19.1	26.1
France	41.7	1.8	1.7	15.3	22.8
Italy	36.9	2.8	1.4	15.6	19.6
United Kingdom	12.9	1.2	1.8	21.4	27.7
Canada	17.0	2.7	1.9	20.0	25.5
Australia	7.2	4.9	2.0	14.8	18.6
Austria	24.1	3.6	2.3	30.8	38.9
Belgium	37.7	2.1	1.5	43.9	88.2
Denmark	20.1	2.3	1.9	30.9	31.1
Finland	45.4	4.5	2.2	26.8	25.4
Greece	25.2	18.7	1.7	17.0	32.0
Ireland	37.7	3.7	2.3	42.1	56.1
Israel	41.3	7.3	1.6	50.0	52.0
Netherlands	26.0	1.5	1.9	45.1	53.9
New Zealand	–5.1	2.1	2.3	25.5	22.6
Norway	56.6	4.0	2.0	45.3	37.7
Portugal	32.4	2.0	1.4	33.6	44.9
Spain	18.7	7.0	1.2	14.7	21.4
Sweden	–14.1	3.5	1.9	22.8	31.6
Switzerland	6.3	1.3	1.9	39.1	38.3

Source: Tables A1, A3, A5 and A6.

Figure 1

(Total Factor Productivity)

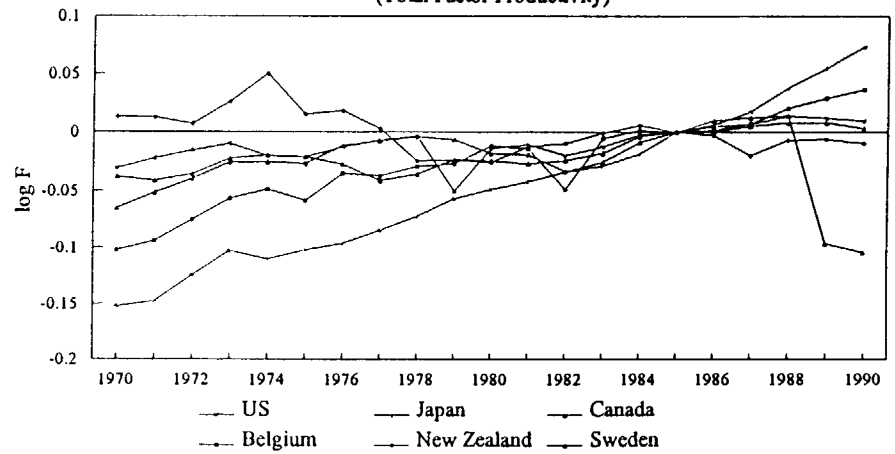
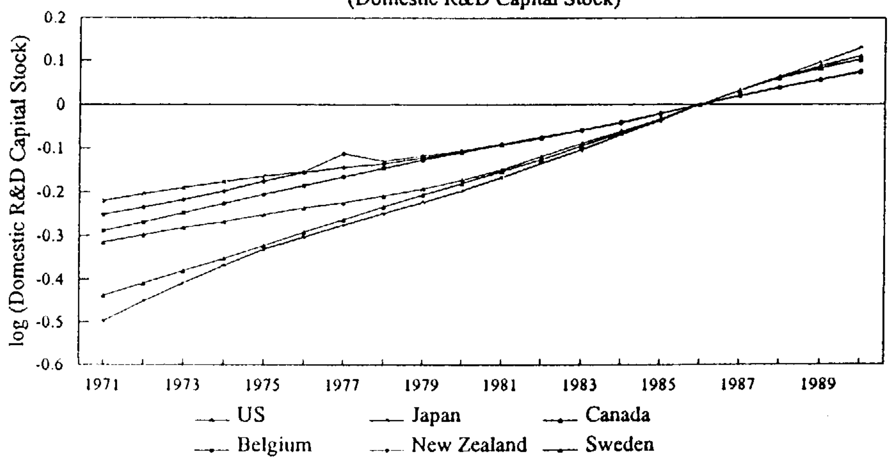


Figure 2

(Domestic R&D Capital Stock)



and Norway. Two countries, the United Kingdom and Switzerland, experienced the slowest expansion of their domestic R&D capital stock (20% and 30%, 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 Figure 2.

Overall changes in foreign R&D capital stocks were less dramatic than in the domestic R&D capital stocks. Here the United State experienced the fastest expansion; more than threefold. At the same time Spain faced the smallest increase (only 20%). 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 capital stocks, as can be seen by comparing Figure 3 with Figure 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%) while Japan had the smallest (9.3%). And as shown in Figure 4, import shares fluctuated over time.

4. EMPIRICAL FINDINGS

We are interested in estimating the long–run relationship between total factor productivity and the foreign and domestic R&D capital stocks. Because almost all of our data exhibit a clear trend, and given our focus on the long–run relationship between total factor productivity and the foreign and domestic R&D capital stocks, we seek to

Figure 3

(Trade Weighted Foreign R&D Capital Stock)

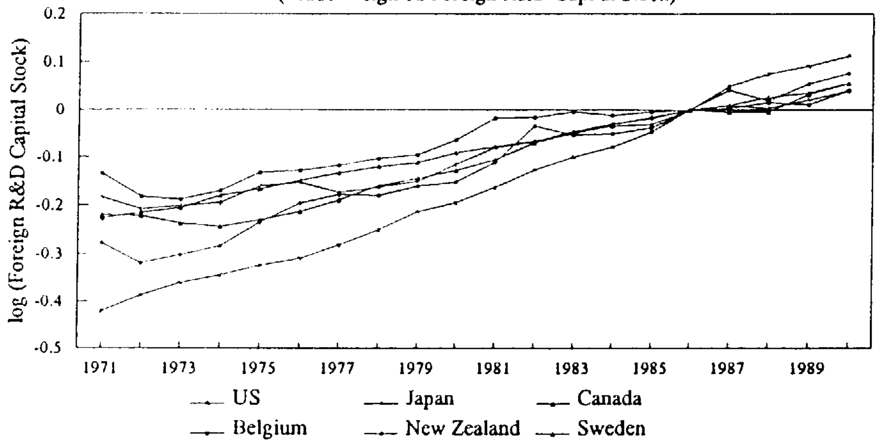
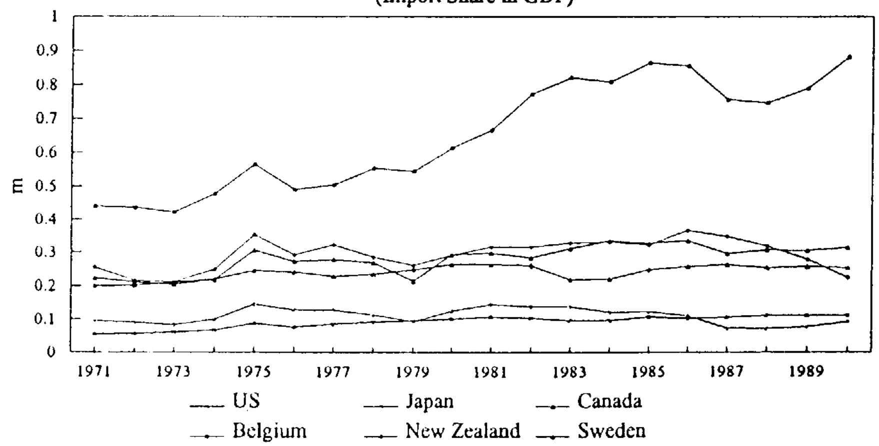


Figure 4

(Import Share in GDP)



estimate equations that are cointegrated.[8] The basic idea of cointegration is that two or more variables may be regarded as defining a long–run equilibrium relationship if they move closely together in the long run, even if they may drift apart in the short run. Given that there is a long–run relationship between the 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]).

Cointegrated equations have very 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. This property is referred to as "super consistency" (Stock [1987]).[9] Moreover, super consistency does not require the assumptions of the classical regression model. This is reassuring, because our estimates of R&D capital stocks are likely to be measured with some degree of error given the need to calculate benchmarks, assume obsolescence rates, and so on; and because we can not exclude that there are omitted relevant variables, such as proxies for the stock of human capital.

Cointegration techniques have been widely applied to time–series data. The implications of our models of international R&D spillovers, however, can only be persuasively verified with panel data. Although the econometrics of pooled

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[8] Cuthbertson, Hall and Taylor (1992) present a useful survey of cointegration; see also Engle and Granger (1987) and Stock (1987).

[9] The intuition behind the superconsistency result is that, for values of the parameters which do not cointegrate the nonstationary series, the residual series will itself be nonstationary and therefore have a very large estimated variance. When the estimated parameters are close to the true cointegrating parrameters, the residual becomes stationary and its variance shrinks. Since ordinary least squares essentially minimize the residual variance, it will be extremely good at picking out the cointegrating parameters if they exist.

cointegration are only now being developed, we conjecture that the super consistency result will hold or be strengthened with pooled data, and that the efficiency of the OLS estimates will increase substantially as the number of countries increases. In our case, we have 1970–1990 data for 22 countries, giving 440 pooled observations. We interpret our estimates as pooled cointegrating equations, even though this means that there may be ambiguity in the interpretation of some of the econometric results. Except for Khan and Reinhart (1993), we are not aware of any applications of cointegrating techniques to panel data.

There are two preliminary issues to discuss before turning to the estimation results. The first concerns the nonstationarity of the variables in the cointegrating equation. The Dickey Fuller and the augmented Dickey Fuller tests on the time series for each country 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) 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 cross–section dimension increases. Unit root tests on the pooled data confirm that the variables are nonstationary, with the possible exception of m, as shown in the upper panel of Table 2.

The second issue concerns the estimated standard errors. Because the variables are nonstationary, the standard errors — and hence the significance tests — will only be unbiased if the independent variables are strictly exogenous (Cuthbertson et al. [1992, p.139]). For the two R&D capital stocks, we would expect this to be so since the equation relates total factor productivity to both stocks at the beginning of the year. Granger causality tests on the pooled data, however, give mixed results (see the lower panel in Table 2). Although it is possible to reject the null hypothesis that total factor productivity does no "cause" — in the sense that it does not "predict" — the import share or the domestic R&D stock (in the later case at the 5 percent level), the null

TABLE 2: POOLED UNIT–ROOT AND EXOGENEITY TESTS

	Test Statistics			Critical Values	
	DF	ADF	F(lags)	5 percent	10 percent
Unit–Root Tests[1]					
F	–5.09	–3.93			
S^d	–2.43	0.73			
S^f	–1.62	–3.00		–7.07	–6.78
$S^f * m$	–2.03	–2.06			
m	–7.68	–5.65			
Exogeneity Tests[2]					
ΔS^d			2.48 (3)	2.60	2.08
ΔS^f			6.53 (4)	2.37	1.94
$\Delta(S^f * m)$			11.20 (3)	2.60	2.08
Δm			0.76 (3)	2.60	2.08

[1]Annual data 1972–1990 for 22 countries, 418 observations. The critical values for the unit root test are from Levin and Lin (1992), Table 5.

[2]Annual data 1973–1990 for 22 countries, 396 observations. The test statistics are based on regressions with ΔX ($X = \log S^d$, $\log S^f$, $\log S^f * m$, and m) as the dependent variable and either 3 or 4 lagged values of $\Delta \log F$ and ΔX as the independent variables (the fourth lag was included if it was significantly different from zero). The Granger causality test is an F–test on the joint significance of all the lagged values of $\Delta \log F$. If the estimated coefficients on the lagged values of $\Delta \log F$ are insignificantly different from zero, X is strictly exogenous.

F = log of total factor productivity.
S^d = log of domestic R&D capital stock, beginning of year.
S^f = log of foreign R&D capital stock, beginning of year.
m = ratio of imports of goods and services to GDP.

hypothesis can not be rejected in the case of the foreign R&D Stock. Given these mixed results, only limited confidence can be placed on the estimated standard errors. In any event, the super consistency of the OLS estimator and our large sample diminishes the importance of confidence intervals and tests of hypotheses.

We report in Table 3 seven pooled cointegrating regressions based on equations (5) and (6), all of which include unreported country–specific constants. 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 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 constraint is dropped in equations (iv) through (vii) 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 in the theory section). Equations (iii), (v), and (vii) include the ratio of imports to GDP as an additional independent variable, but we cannot reject the hypothesis that the import share has no independent effect on total factor productivity

[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). The estimated coefficient on this variable was not significantly different from zero. Allowing the impact of domestic R&D on total factor productivity to differ between small and large countries is supported by the data, with the result being that the impact is larger in the large countries. This may result from 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 spill over to foreign countries.

TABLE 3: TOTAL FACTOR PRODUCTIVITY ESTIMATION RESULTS
Pooled Data 1971–90 for 22 countries, 440 observations
(Standard errors in parentheses)

	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)
$\log S^d$	0.095	0.088	0.085	0.073	0.072	0.085	0.083
	(0.010)	(0.009)	(0.009)	(0.008)	(0.009)	(0.009)	(0.009)
$\log S^d * G7$		0.141	0.143	0.159	0.160	0.194	0.196
		(0.017)	(0.018)	(0.016)	(0.016)	(0.018)	(0.018)
$\log S^f$	0.082	0.048	0.045			–0.109	–0.112
	(0.017)	(0.016)	(0.016)			(0.028)	(0.028)
$\log S^f * m$				0.273	0.268	0.531	0.530
				(0.045)	(0.045)	(0.080)	(0.080)
m			0.073		0.057		0.070
			(0.053)		(0.051)		(0.050)
Standard error	0.053	0.049	0.049	0.048	0.048	0.047	0.047
R^2	0.498	0.566	0.568	0.594	0.595	0.608	0.610
R^2 adjusted	0.470	0.541	0.542	0.570	0.571	0.584	0.585
Augmented Dickey–Fuller	–5.955	–6.083	–5.865	–6.444	–6.239	–6.496	–6.190

The dependent variable is log (total factor productivity). All equations include unreported, country–specific constants.

S^d = log of domestic R&D capital stock, beginning of year
S^f = log of foreign R&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.

(except for its interaction with the foreign R&D capital stock).[11]

The estimated equations explain over half of the variance in the 440 observations, with all of the coefficients of the expected sign and, except for those on m, highly significant. The magnitudes of the estimated elasticities are plausible, and remarkably stable across the different specifications, particularly in the specifications that include $\log S^f * G7$.[12] For the non G7 countries, the estimated elasticities of TFP with respect to the domestic R&D stock are similar to those typically found in single–country studies (as summarized in Griliches [1988]). For the G7 countries, however, the estimated elasticities of TFP with respect to the domestic R&D stock are considerably larger than those from studies that do not include international R&D spillovers. Our rich cross–country data and our estimation procedure that focuses on the identification of long–run relationships are probably better able to estimate the social return to R&D than are single–country studies.

Levin and Lin's critical values for pooled augmented Dickey–Fuller unit root tests can be used to test the stationarity of the residuals of our pooled cointegrating regressions. At the 10 percent confidence level, the critical value for the augmented

[11] Recall, however, the caveat about significance tests made above. 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 (iv), for example, increases from 0.478 to 0.570 (and the unadjusted R^2 increases similarly) 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. Adding dummy variables for 19 of the 20 years (in addition to the country–specific constants) tends to decrease the size of the estimated parameters (as one would expect), but they remain significantly different from zero [the coefficients corresponding to column (iv) in Table 3 (from top to bottom) obtain the values 0.0330, 0.1181 and 0.1240, respectively, with standard errors 0.0121, 0.0189, and 0.0647, respectively]. This suggests that our R&D capital stock variables contribute to the explanation of TFP not merely as proxies for prevailing time trends, and that they play an important role even if there existed time specific shocks that were common to all countries.

[12] As previously noted, we think that the implications of our models can only be verified on panel data. Tests of whether the cross–country parameter restrictions implied by our specifications are accepted by the data for single countries are rejected.

Dickey–Fuller test reported by Levin and Lin is –6.78, which is only marginally higher than the ADF test statistics on the residuals of the estimated equations reported in Table 3. We conclude that the estimated equations are cointegrated, or very nearly so.[13]

Equation (iv) is econometrically the most interesting and theoretically consistent with our model. In this equation, the impact of the foreign R&D capital stock varies across all countries and over time. Table 4 reports the estimated elasticities of total factor productivity with respect to the foreign R&D capital stocks — which is simply the estimated coefficient from Table 3 multiplied by the import share — for 1971, 1980 and 1990.[14] With the notable exception of Norway, the estimated impact of foreign R&D rises, usually by a substantial amount from 1971 to 1980. In the United Kingdom, Greece, Portugal, Spain, and especially Belgium, the estimated impact of foreign R&D rises further during the 1980s. Although the domestic R&D capital stock has a 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 and Spain. Foreign R&D has the strongest impact on Belgium, followed by Ireland, Israel and the Netherlands.

Estimates of the international R&D spillovers are presented in Table 5. Each entry is the estimated elasticity of total factor productivity in the country indicated in

[13] The ADF test statistics on the residuals of estimated equations including year dummies are about 1.2 smaller (in absolute value) than the ADF test statistics reported in Table 3 (for our most preferred equation (iv) it is –5.101), suggesting that the evidence for cointegration is stronger in the equations excluding the year dummies.

[14] The general pattern of the relative importance of domestic versus foreign R&D stocks that is exhibited in Table 4 does not change significantly when one uses equation (vi) or (vii) instead of (iv). In the former case the signs and magnitudes of the estimated coefficients on the foreign R&D stock alone and interacted with the import share must be considered together. The main difference that emerges, however, is that for counties with import shares of about 0.2 or less the use of (vi) or (vii) implies very small negative effects.

TABLE 4: COUNTRY–SPECIFIC, TIME–VARYING ESTIMATES OF THE IMPACT OF R&D CAPITAL STOCKS ON TOTAL FACTOR PRODUCTIVITY

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	0.263	0.016	0.030	0.030	
Japan	0.260	0.025	0.041	0.027	
West Germany	0.301	0.052	0.074	0.068	
France	0.296	0.041	0.063	0.063	0.233
Italy	0.288	0.041	0.066	0.055	
United Kingdom	0.306	0.057	0.068	0.073	
Canada	0.304	0.055	0.071	0.071	
Australia	0.123	0.038	0.049	0.049	
Austria	0.181	0.082	0.106	0.107	
Belgium	0.320	0.120	0.183	0.246	
Denmark	0.156	0.079	0.093	0.082	
Finland	0.140	0.071	0.096	0.066	
Greece	0.164	0.046	0.063	0.090	
Ireland	0.219	0.109	0.153	0.145	0.074
Israel	0.216	0.136	0.143	0.142	
Netherlands	0.216	0.123	0.145	0.142	
New Zealand	0.156	0.060	0.087	0.082	
Norway	0.175	0.123	0.118	0.101	
Portugal	0.197	0.090	0.112	0.123	
Spain	0.129	0.038	0.049	0.055	
Sweden	0.156	0.057	0.082	0.082	
Switzerland	0.172	0.098	0.109	0.098	

Based on equation (iv) in Table 3.

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	—	.0203	.0036	.0013	.0005	.0022	.0022
Japan	.0237	—	.0007	.0003	.0001	.0003	.0001
West Germany	.0432	.0091	—	.0076	.0023	.0056	.0001
France	.0343	.0046	.0145	—	.0023	.0045	.0001
Italy	.0236	.0025	.0155	.0071	—	.0030	.0001
United Kingdom	.0492	.0064	.0122	.0043	.0011	—	.0002
Canada	.0669	.0018	.0005	.0002	.0001	.0005	—
Australia	.0380	.0085	.0018	.0005	.0002	.0016	.0001
Austria	.0280	.0095	.0567	.0038	.0031	.0028	.0001
Belgium	.0864	.0108	.0754	.0315	.0036	.0213	.0004
Denmark	.0418	.0058	.0232	.0034	.0011	.0062	.0001
Finland	.0331	.0096	.0153	.0025	.0011	.0049	.0001
Greece	.0270	.0128	.0267	.0060	.0053	.0066	.0001
Ireland	.0959	.0087	.0088	.0027	.0007	.0351	.0001
Israel	.1104	.0042	.0113	.0028	.0016	.0077	.0001
Netherlands	.0773	.0069	.0399	.0078	.0015	.0104	.0002
New Zealand	.0429	.0121	.0019	.0004	.0002	.0033	.0002
Norway	.0598	.0078	.0172	.0030	.0011	.0089	.0005
Portugal	.0504	.0087	.0273	.0145	.0046	.0119	.0003
Spain	.0333	.0044	.0091	.0056	.0017	.0034	.0001
Sweden	.0460	.0085	.0189	.0033	.0010	.0065	.0001
Switzerland	.0421	.0075	.0372	.0079	.0030	.0053	.0001
Average elasticity of foreign total factor productivity	.0392	.0129	.0084	.0030	.0009	.0031	.0010
Elasticity of domestic total factor productivity	.2327	.2327	.2327	.2327	.2327	.2327	.2327
Average elasticity of total factor productivity in all 22 countries	.1188	.0436	.0259	.0177	.0153	.0176	.0102

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 (iv) in Table 3.
Averages are calculated using PPP–based GDP weights.

the row with respect to the R&D capital stock in the country indicated in the column.[15] 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. This, of course, is only the first–round supply–side effect, which will be magnified via foreign trade multipliers.

The United States has the strongest effect on Israel and Ireland (elasticities of 0.1104 and 0.0959, respectively) while Japan has the strongest effect on the United States. Germany has the strongest effect on Belgium and Austria, France has the strongest effect on Belgium, Italy has the strongest effect on Greece, and the United Kingdom has the strongest effect on Ireland.

The last row 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 0.044 percent. This difference reflects partly the fact that the United States has an R&D capital stock which is about four times as large as Japan's R&D capital stock.

[15] When the R&D capital stock of country i, S^d_i, increases by 1%, the foreign R&D capital stock of country j, S^f_j, rises by $m^j_i S^d_i / \Sigma_{k \neq j} m^j_k S^d_k$ percent and country j's output rises my $m^j \alpha^f m^j_i S^d_i / \Sigma_{k \neq j} m^i_k S^d_k$ percent, where m^j is country j's import share and m^j_i is the fraction of j's imports coming from country i. The last formula was used to compute the numbers in Table 5.

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:

$$\rho_{ij} = \alpha_{ij} \frac{Y_i}{S_j^d}, \tag{7}$$

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 that we can calculate for individual countries because the coefficient α^d was estimated to be equal across countries within each group.[16]

[16] It follows from (7) that the own rate of return is given by $\rho_{jj} = \alpha_j^d Y_j/S_j^d$ and that the worldwide 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_C^d. For this group of countries the average own rate of return equals $\rho_{CC} \equiv \Sigma_{j\epsilon C} \rho_{jj} S_j^d/(\Sigma_{i\epsilon C} S_i^d) = \alpha_C^d \Sigma_{j\epsilon C} Y_j/\Sigma_{j\epsilon C} S_j^d$. On the other hand, the average worldwide rate of return for this group of countries equals $\rho_C \equiv \Sigma_{j\epsilon C} \rho_j S_j^d/(\Sigma_{i\epsilon C} S_i^d)$.

Our calculations (based on the data in Tables A4 and A7) show that in 1990 the average own rate of return from investment in R&D was 121.9% in the G7 countries and 80.7% 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 $121.9 on average, and that a $100. increase in the R&D capital stock of one of the smaller 15 countries raises its GDP by $80.7 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 152.1%. 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%, which implies a large international R&D spillover; about one quarter of the benefits of R&D investment in a G7 country occur 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.

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 [1993] 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.[17] 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 has a stronger effect on domestic productivity the more open an economy is to intentional trade. 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 R&D capital stocks is very high, both in terms of domestic output and in

[17] There are some exceptions to this statement, such as Englander, Evanson and Hamazaki (1988) and Helliwell (1992).

terms of international spillovers.

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

APPENDIX

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 1987–1989. 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 A1 and the capital shares are reported in Table A2.

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*.[18] Real R&D expenditures are nominal expenditures deflated by an R&D price index (PR), which is defined as

[18] R&D capital stocks were also calculated based on gross (business enterprises plus government) domestic expenditures on R&D for all countries except Israel (for which data are not available). For the United States and Israel, R&D capital stocks were also calculated based on privately financed R&D expenditures performed by business enterprises.

TABLE A1: TOTAL FACTOR PRODUCTIVITY

(1985 = 1)

	U.S.	Japan	Germany	France	Italy	U.K.	Canada
1970	0.932	0.704	0.861	0.782	0.770	0.805	0.861
1971	0.950	0.712	0.873	0.807	0.771	0.823	0.888
1972	0.965	0.750	0.869	0.829	0.791	0.843	0.912
1973	0.978	0.769	0.913	0.856	0.835	0.867	0.943
1974	0.954	0.776	0.904	0.863	0.858	0.862	0.943
1975	0.952	0.790	0.900	0.854	0.817	0.852	0.940
1976	0.972	0.801	0.944	0.877	0.863	0.878	0.974
1977	0.984	0.823	0.956	0.892	0.879	0.891	0.983
1978	0.992	0.847	0.976	0.913	0.903	0.913	0.991
1979	0.981	0.878	0.997	0.936	0.946	0.925	0.966
1980	0.969	0.894	0.980	0.941	0.969	0.905	0.959
1981	0.976	0.907	0.966	0.946	0.966	0.914	0.956
1982	0.955	0.925	0.946	0.965	0.961	0.941	0.926
1983	0.972	0.936	0.964	0.967	0.963	0.977	0.943
1984	0.995	0.958	0.990	0.983	0.963	0.976	0.980
1985	1	1	1	1	1	1	1
1986	1.011	1.014	0.999	1.020	1.015	1.035	1.002
1987	1.016	1.041	0.995	1.036	1.040	1.062	1.011
1988	1.032	1.091	1.017	1.070	1.067	1.072	1.019
1989	1.029	1.134	1.037	1.096	1.090	1.059	1.019
1990	1.022	1.185	1.056	1.108	1.054	0.909	1.007

	Aus'lia	Austria	Belgium	Denmark	Finland	Greece	Ireland
1970	0.877	0.866	0.790	0.842	0.779	0.829	0.808
1971	0.885	0.891	0.805	0.846	0.784	0.867	0.825
1972	0.890	0.923	0.841	0.881	0.839	0.920	0.876
1973	0.916	0.942	0.878	0.894	0.871	0.956	0.888
1974	0.900	0.958	0.894	0.869	0.864	0.898	0.905
1975	0.899	0.945	0.874	0.871	0.859	0.937	0.919
1976	0.917	0.973	0.922	0.913	0.831	0.975	0.916
1977	0.904	0.991	0.918	0.911	0.834	0.987	0.958
1978	0.931	0.965	0.935	0.909	0.855	1.037	0.980
1979	0.948	0.990	0.940	0.928	0.902	1.050	0.964
1980	0.940	0.999	0.974	0.918	0.925	1.040	0.967
1981	0.951	0.974	0.968	0.912	0.924	0.986	0.968
1982	0.932	0.963	0.984	0.937	0.945	0.982	0.960
1983	0.935	0.981	0.988	0.956	0.963	0.967	0.947
1984	0.982	0.984	1.004	0.983	0.980	0.984	0.976
1985	1	1	1	1	1	1	1
1986	0.963	0.991	1.004	1.008	1.025	1.006	0.974
1987	1.002	0.997	1.017	0.988	1.065	0.998	1.018
1988	0.999	1.027	1.048	0.984	1.108	1.024	1.035
1989	1.003	1.051	1.069	0.995	1.148	1.046	1.080
1990	0.940	1.075	1.088	1.011	1.133	1.038	1.110

	Israel	Nether.	N.Z.	Norway	Portugal	Spain	Sweden	Switz.
1970	0.806	0.818	1.031	0.668	0.863	0.894	0.916	0.932
1971	0.858	0.836	1.030	0.691	0.869	0.899	0.909	0.949
1972	0.905	0.865	1.017	0.719	0.945	0.935	0.921	0.962
1973	0.922	0.866	1.062	0.746	1.040	0.957	0.950	0.976
1974	0.943	0.909	1.122	0.777	0.976	0.963	0.955	0.976
1975	0.952	0.897	1.035	0.790	0.879	0.942	0.952	0.937
1976	0.931	0.933	1.043	0.809	0.922	0.948	0.939	0.945
1977	0.920	0.948	1.007	0.818	0.960	0.955	0.909	0.959
1978	0.924	0.952	0.945	0.838	0.980	0.954	0.921	0.951
1979	0.920	0.955	0.947	0.873	1.023	0.938	0.948	0.961
1980	0.948	0.947	0.943	0.904	1.044	0.949	0.945	0.962
1981	0.976	0.941	0.972	0.889	1.040	0.946	0.940	0.970
1982	0.966	0.937	0.978	0.883	1.062	0.950	0.946	0.950
1983	0.963	0.960	0.998	0.928	0.994	0.961	0.959	0.955
1984	0.959	0.990	1.013	0.969	0.965	0.980	0.992	0.959
1985	1	1	1	1	1	1	1	1
1986	1.037	0.999	0.994	1.001	1.039	1.008	1.023	1.038
1987	1.080	0.987	0.955	0.995	1.066	1.033	1.029	1.041
1988	1.095	0.997	0.984	0.992	1.084	1.061	1.033	1.054
1989	1.097	1.018	0.987	1.019	1.120	1.057	0.801	0.983
1990	1.139	1.031	0.978	1.048	1.143	1.061	0.787	0.991

TABLE A2: CAPITAL SHARES, R&D CAPITAL STOCK BENCHMARKS, AND PPP EXCHANGE RATES

	Capital share β	R&D ependiture Available	R&D ependiture Avg. Gro.	R&D stock benchmark	PPP exchange rates – 1985
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
UK	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	2,632	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

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.

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

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 1970–1990 period (see Table A2), in which case an estimated equation relating real R&D 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.[19] The benchmark for S was calculated following the procedure suggested by Griliches (1980), as

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

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

[19] Alternative measures of the R&D capital stocks were also calculated assuming $\delta = 0$ and $\delta = 0.1$. Experimental time–series regressions using these alternative capital stocks yielded similar results to those with $\delta = 0.05$.

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 Schultz–Ghattas (1992). The calculated benchmarks and PPP exchange rates are reported in Table A2, and the estimates of the domestic R&D capital stocks are reported in Table A3.

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 1970–1990 based on data from the IMF's *Direction of Trade*. The bilateral import–share weighting matrix for 1985 is reported in Table A4, and estimates of the import–share weighted foreign R&D capital stocks are reported in Table A5. 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 World Economic Outlook database, are reported in Table A6.

TABLE A3: DOMESTIC R&D CAPITAL STOCK

(In U.S. Dollars, 1986 = 1)

	U.S.	Japan	Germany	France	Italy	U.K.	Canada	Aus'lia	Austria	Belgium	Denmark	Finland	Greece	Ireland	Israel	Nether.	N.Z.	Norway	Portugal	Spain	Sweden	Switz.
1971	0.602	0.318	0.463	0.634	0.463	0.853	0.485	0.323	0.341	0.515	0.551	0.308	0.082	0.372	0.245	0.775	0.561	0.344	0.630	0.214	0.365	0.858
1972	0.624	0.353	0.496	0.656	0.499	0.859	0.504	0.336	0.371	0.538	0.577	0.341	0.101	0.406	0.271	0.794	0.582	0.369	0.657	0.245	0.390	0.872
1973	0.645	0.390	0.526	0.680	0.535	0.864	0.523	0.356	0.408	0.565	0.602	0.378	0.125	0.438	0.301	0.814	0.608	0.396	0.684	0.279	0.416	0.884
1974	0.668	0.429	0.556	0.701	0.565	0.873	0.540	0.391	0.444	0.593	0.626	0.410	0.152	0.465	0.330	0.828	0.634	0.425	0.706	0.323	0.444	0.895
1975	0.685	0.466	0.583	0.723	0.594	0.882	0.560	0.426	0.478	0.623	0.647	0.443	0.177	0.492	0.360	0.845	0.667	0.454	0.717	0.378	0.476	0.904
1976	0.703	0.499	0.613	0.744	0.625	0.885	0.580	0.460	0.511	0.652	0.667	0.475	0.217	0.521	0.385	0.860	0.698	0.490	0.719	0.434	0.511	0.914
1977	0.772	0.531	0.641	0.765	0.652	0.893	0.597	0.504	0.550	0.683	0.689	0.507	0.264	0.550	0.421	0.875	0.718	0.527	0.716	0.491	0.546	0.922
1978	0.742	0.564	0.670	0.786	0.679	0.903	0.617	0.546	0.592	0.715	0.712	0.541	0.311	0.579	0.479	0.886	0.732	0.566	0.711	0.543	0.583	0.927
1979	0.763	0.597	0.706	0.807	0.703	0.915	0.641	0.588	0.639	0.747	0.737	0.581	0.369	0.614	0.531	0.897	0.764	0.604	0.704	0.590	0.621	0.935
1980	0.786	0.636	0.748	0.829	0.733	0.928	0.672	0.634	0.688	0.777	0.762	0.623	0.422	0.650	0.578	0.908	0.779	0.647	0.723	0.635	0.659	0.943
1981	0.812	0.681	0.786	0.853	0.765	0.941	0.710	0.683	0.740	0.808	0.791	0.671	0.477	0.697	0.620	0.920	0.812	0.689	0.754	0.689	0.702	0.950
1982	0.842	0.733	0.827	0.879	0.804	0.954	0.761	0.732	0.791	0.838	0.821	0.720	0.533	0.749	0.653	0.933	0.845	0.734	0.796	0.732	0.749	0.956
1983	0.874	0.788	0.867	0.907	0.845	0.966	0.816	0.778	0.842	0.874	0.857	0.778	0.627	0.801	0.701	0.945	0.874	0.785	0.841	0.792	0.803	0.961
1984	0.910	0.851	0.907	0.935	0.890	0.975	0.868	0.826	0.895	0.914	0.809	0.840	0.745	0.851	0.748	0.960	0.906	0.842	0.893	0.847	0.861	0.968
1985	0.952	0.920	0.952	0.966	0.939	0.987	0.927	0.901	0.947	0.956	0.947	0.916	0.871	0.918	0.929	0.976	0.951	0.913	0.945	0.913	0.927	0.980
1986	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1987	1.046	1.077	1.049	1.034	1.068	1.018	1.078	1.131	1.051	1.044	1.060	1.069	1.128	1.090	1.229	1.032	1.046	1.092	1.054	1.106	1.072	1.024
1988	1.091	1.158	1.100	1.070	1.134	1.036	1.150	1.265	1.104	1.089	1.124	1.183	1.261	1.184	1.440	1.068	1.090	1.184	1.111	1.216	1.142	1.047
1989	1.136	1.248	1.150	1.108	1.208	1.053	1.222	1.416	1.183	1.135	1.191	1.284	1.396	1.279	1.616	1.100	1.137	1.275	1.173	1.356	1.207	1.070
1990	1.176	1.345	1.203	1.149	1.288	1.066	1.289	1.581	1.231	1.189	1.259	1.392	1.530	1.378	1.796	1.133	1.185	1.365	1.243	1.505	1.283	1.091

TABLE A4: BILATERAL IMPORT SHARES

(Percent of total imports from countries listed, 1990)

	United States	Japan	Germany	France	Italy	UK	Canada	Australia	Austria	Belgium	Denmark	Finland	Greece	Ireland	Israel	Netherland	New Zealand	Norway	Portogal	Spain	Sweden	Switz.
United States		45.77	9.43	9.55	7.23	13.26	75.93	29.78	4.30	6.27	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	6.56	8.49		24.06	28.12	19.46	3.19	8.32	51.76	27.34	26.48	22.06	24.95	9.42	12.96	31.01	6.24	15.66	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	17.38	6.89	5.39	8.52	4.41	4.85	9.20	1.87	4.26	14.04	17.90	6.06	12.06
Italy	4.26	3.59	11.15	14.29		6.52	1.73	4.00	10.84	4.94	4.69	6.93	18.69	2.84	8.95	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	9.18	8.30	8.36	7.27	44.55	10.49	9.59	11.01	9.68	8.96	6.51	9.22	6.24
Canada	29.94	8.16	1.07	0.90	1.00	2.22		3.16	0.56	0.77	0.62	1.11	0.59	0.83	0.81	0.92	2.45	2.62	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	0.66	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	0.88		3.97	1.60	1.00	0.52	1.38	0.53	8.68	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	0.78	0.87	7.69	0.73
Greece	0.16	0.17	0.84	0.51	1.53	0.38	0.06	0.22	0.51	0.22	0.34	0.38		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	0.48	0.45	0.82	0.76	0.81	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	3.28	20.45	8.81	4.09	9.07	4.46	4.16		1.43	4.32	6.59	4.29	4.79	4.61
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		0.06	0.08	0.16	0.06	0.05
Norway	0.71	0.53	1.80	1.76	0.52	3.63	0.66	0.68	0.46	0.95	6.20	2.96	0.51	0.41	0.26	1.62	0.33		1.08	0.68	7.86	0.66
Portogal	0.26	0.16	0.99	1.26	0.61	1.01	0.14	0.16	0.67	0.45	1.19	1.07	0.48	0.60	0.31	0.72	0.15	1.54		3.05	1.30	0.41
Spain	1.20	0.65	2.82	5.46	3.22	2.81	0.49	0.59	1.01	1.65	1.24	1.30	2.36	1.35	1.28	1.58	0.42	1.43	17.87		1.24	1.20
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
Switz.	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	0.89	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

Source: IMF data base.

TABLE A5: FOREIGN R&D CAPITAL STOCK

(In U.S. dollars, weighted by import shares, 1985 = 1)

	U.S.	Japan	Germany	France	Italy	U.K.	Canada	Aus'lia	Austria	Belgium	Denmark
1971	0.379	0.654	0.768	0.672	0.787	0.647	0.593	0.613	0.518	0.733	0.652
1972	0.410	0.619	0.757	0.634	0.741	0.590	0.609	0.577	0.555	0.656	0.714
1973	0.435	0.628	0.682	0.641	0.726	0.587	0.622	0.584	0.555	0.648	0.670
1974	0.452	0.638	0.713	0.671	0.750	0.605	0.660	0.627	0.561	0.675	0.672
1975	0.472	0.690	0.735	0.717	0.797	0.634	0.680	0.638	0.579	0.737	0.681
1976	0.489	0.701	0.740	0.713	0.864	0.644	0.708	0.645	0.601	0.744	0.690
1977	0.523	0.670	0.779	0.722	0.838	0.680	0.734	0.671	0.631	0.762	0.669
1978	0.562	0.687	0.729	0.727	0.819	0.714	0.757	0.701	0.652	0.788	0.722
1979	0.612	0.705	0.763	0.753	0.824	0.713	0.772	0.758	0.684	0.802	0.735
1980	0.638	0.767	0.787	0.801	0.852	0.729	0.810	0.798	0.727	0.863	0.745
1981	0.686	0.830	0.872	0.879	0.901	0.850	0.835	0.827	0.778	0.961	0.837
1982	0.748	0.854	0.921	0.935	0.949	0.857	0.858	0.898	0.662	0.962	1.016
1983	0.793	0.900	0.931	0.939	0.975	0.884	0.869	0.903	0.676	0.990	0.938
1984	0.833	0.934	0.919	0.946	0.937	0.903	0.930	0.928	0.665	0.972	0.876
1985	0.897	0.957	0.975	0.980	0.972	0.965	0.968	0.963	0.935	0.988	0.902
1986	1	1	1	1	1	1	1	1	1	1	1
1987	1.119	1.019	0.993	1.012	0.970	0.960	1.022	1.031	1.010	1.006	1.015
1988	1.189	1.008	1.016	1.029	0.977	0.997	1.060	1.077	1.065	1.035	1.046
1989	1.234	1.047	1.102	1.122	1.033	1.059	1.085	1.127	1.121	1.026	1.135
1990	1.295	1.097	1.238	1.163	1.063	1.177	1.135	1.223	1.168	1.095	1.248

	Finland	Greece	Ireland	Israel	Nether.	N.Z.	Norway	Portugal	Spain	Sweden	Switz.
1971	0.556	0.661	0.492	0.639	0.593	0.528	0.585	0.504	0.722	0.602	0.646
1972	0.538	0.701	0.536	0.676	0.614	0.478	0.562	0.617	0.673	0.600	0.619
1973	0.635	0.724	0.522	0.603	0.584	0.498	0.578	0.609	0.689	0.579	0.633
1974	0.557	0.673	0.508	0.633	0.631	0.520	0.625	0.571	0.716	0.571	0.633
1975	0.613	0.967	0.509	0.672	0.680	0.582	0.735	0.652	0.786	0.587	0.666
1976	0.659	0.865	0.546	0.636	0.744	0.637	0.698	0.803	0.834	0.611	0.735
1977	0.657	0.904	0.563	0.602	0.744	0.662	0.693	0.677	0.822	0.647	0.738
1978	0.675	0.834	0.608	0.742	0.746	0.660	0.717	0.748	0.784	0.691	0.763
1979	0.715	0.879	0.607	0.721	0.761	0.689	0.745	0.809	0.848	0.717	0.825
1980	0.751	0.910	0.621	0.829	0.793	0.703	0.796	0.856	0.829	0.743	0.826
1981	0.865	0.948	0.649	0.887	0.844	0.774	0.886	0.874	0.953	0.783	0.856
1982	1.023	0.968	0.734	0.954	0.918	0.922	0.983	0.957	1.049	0.850	0.917
1983	0.942	0.976	0.784	0.924	0.926	0.884	1.019	0.930	1.050	0.894	0.945
1984	0.950	0.949	0.863	0.935	0.958	0.888	1.032	1.135	0.994	0.922	1.044
1985	0.933	0.942	0.948	1.010	1.000	0.916	1.063	1.182	1.004	0.931	1.000
1986	1	1	1	1	1	1	1	1	1	1	1
1987	0.958	0.991	1.001	0.921	0.981	1.099	1.018	0.788	0.862	0.990	1.022
1988	1.048	0.965	1.086	0.879	0.980	1.046	1.001	0.693	0.798	0.988	1.069
1989	1.167	1.096	1.094	0.904	1.044	1.134	1.067	0.687	0.843	1.078	1.131
1990	1.205	1.110	1.133	1.001	1.140	1.190	1.196	0.692	0.877	1.136	1.230

TABLE A6: IMPORTS AS A SHARE OF GDP

(Ratio)

	U.S.	Japan	Germany	France	Italy	U.K.	Canada	Aus'lia	Austria	Belgium	Denmark
1971	0.0552	0.0958	0.1914	0.1528	0.1560	0.2145	0.2001	0.1476	0.3061	0.4387	0.3090
1972	0.0568	0.0907	0.1897	0.1534	0.1547	0.2106	0.2008	0.1422	0.2969	0.4362	0.2944
1973	0.0615	0.0835	0.1880	0.1568	0.1628	0.2126	0.2097	0.1217	0.2875	0.4215	0.2650
1974	0.0678	0.1006	0.1891	0.1670	0.1873	0.2552	0.2200	0.1272	0.3071	0.4773	0.3043
1975	0.0874	0.1446	0.2197	0.2170	0.2379	0.3238	0.2456	0.1869	0.3436	0.5638	0.3468
1976	0.0774	0.1286	0.2177	0.1787	0.2010	0.2721	0.2411	0.1430	0.3032	0.4895	0.3102
1977	0.0855	0.1275	0.2342	0.2031	0.2279	0.2924	0.2288	0.1484	0.3413	0.5036	0.3349
1978	0.0924	0.1142	0.2309	0.2036	0.2170	0.2902	0.2352	0.1628	0.3497	0.5534	0.3246
1979	0.0951	0.0938	0.2227	0.1908	0.2089	0.2892	0.2486	0.1632	0.3329	0.5452	0.2995
1980	0.1015	0.1247	0.2441	0.2064	0.2287	0.2742	0.2654	0.1664	0.3610	0.6137	0.3207
1981	0.1085	0.1459	0.2690	0.2275	0.2411	0.2485	0.2644	0.1775	0.3877	0.6679	0.3376
1982	0.1048	0.1393	0.2794	0.2353	0.2483	0.2370	0.2612	0.1787	0.3963	0.7726	0.3581
1983	0.0963	0.1380	0.2747	0.2370	0.2357	0.2430	0.2206	0.1817	0.3839	0.8214	0.3594
1984	0.0984	0.1216	0.2674	0.2286	0.2099	0.2548	0.2214	0.1509	0.3812	0.8089	0.3437
1985	0.1072	0.1227	0.2816	0.2350	0.2253	0.2844	0.2488	0.1720	0.3883	0.8641	0.3545
1986	0.1034	0.1109	0.2901	0.2325	0.2287	0.2787	0.2581	0.1912	0.4055	0.8552	0.3633
1987	0.1058	0.0741	0.2496	0.2016	0.1818	0.2628	0.2637	0.1868	0.3602	0.7563	0.3249
1988	0.1117	0.0723	0.2395	0.2051	0.1826	0.2642	0.2547	0.1782	0.3518	0.7483	0.2961
1989	0.1127	0.0763	0.2434	0.2123	0.1830	0.2848	0.2581	0.1754	0.3694	0.7902	0.2935
1990	0.1119	0.0928	0.2613	0.2278	0.1980	0.2789	0.2548	0.1884	0.3686	0.8819	0.3114

	Finland	Greece	Ireland	Israel	Nether.	N.Z.	Norway	Portugal	Spain	Sweden	Switz.
1971	0.2678	0.1700	0.4212	0.5002	0.4513	0.2548	0.4535	0.3359	0.1468	0.2282	0.3607
1972	0.2591	0.1675	0.4018	0.4964	0.4469	0.2159	0.4500	0.3283	0.1372	0.2108	0.3507
1973	0.2440	0.1587	0.3776	0.4487	0.4109	0.2112	0.4086	0.3100	0.1477	0.2037	0.3400
1974	0.2576	0.1752	0.4236	0.5781	0.4303	0.2491	0.4621	0.3500	0.1566	0.2164	0.3441
1975	0.3252	0.2167	0.5448	0.5517	0.5006	0.3532	0.5133	0.4212	0.1963	0.3067	0.3828
1976	0.2973	0.1819	0.4345	0.5518	0.4613	0.2932	0.5000	0.3580	0.1776	0.2719	0.2827
1977	0.2633	0.1868	0.4842	0.5288	0.4672	0.3231	0.5216	0.3642	0.1859	0.2790	0.3078
1978	0.2512	0.2030	0.5609	0.5020	0.4528	0.2866	0.5171	0.3626	0.1653	0.2699	0.3408
1979	0.2469	0.1962	0.5282	0.5338	0.4437	0.2612	0.4196	0.3647	0.1439	0.2153	0.3266
1980	0.2979	0.2137	0.6112	0.5251	0.4862	0.2934	0.4229	0.3968	0.1472	0.2943	0.3565
1981	0.3480	0.2325	0.5838	0.4788	0.5305	0.3178	0.4266	0.4123	0.1614	0.2968	0.4026
1982	0.3208	0.2487	0.5646	0.5016	0.5446	0.3169	0.3996	0.4485	0.2016	0.2844	0.3838
1983	0.3002	0.2625	0.5432	0.5177	0.5336	0.3304	0.4097	0.4476	0.2067	0.3135	0.3603
1984	0.2982	0.2614	0.5415	0.5374	0.5388	0.3328	0.3851	0.4290	0.2186	0.3355	0.3524
1985	0.2782	0.2993	0.5865	0.5205	0.5690	0.3241	0.3820	0.4451	0.2136	0.3282	0.3806
1986	0.2833	0.3278	0.5761	0.4985	0.5671	0.3679	0.3890	0.4085	0.2119	0.3363	0.3863
1987	0.2514	0.3009	0.5159	0.5280	0.4970	0.3491	0.4147	0.3551	0.1773	0.2974	0.3550
1988	0.2497	0.3200	0.5121	0.5930	0.4959	0.3200	0.3768	0.4088	0.1922	0.3076	0.3472
1989	0.2488	0.3044	0.5278	0.5654	0.5041	0.2805	0.3740	0.4674	0.1997	0.3074	0.3606
1990	0.2538	0.3202	0.5610	0.5196	0.5385	0.2281	0.3767	0.4487	0.2137	0.3162	0.3626

Source: IMF data base.

TABLE A7: GDP AND DOMESTIC R&D CAPITAL STOCK - 1990

	GDP	Sd	GDP/Sd	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	

GDP and R&D cpital stocks are in 1985 US Dollars, based on PPP.

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