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INTERNATIONAL R&D SPILLOVERS BETWEEN U.S. AND JAPANESE R&D INTENSIVE SECTORS

Jeffrey I. Bernstein
Pierre Mohnen

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ABSTRACT

A great deal of empirical evidence shows that a country's production structure and productivity growth depend on its own R&D capital formation. With the growing role of international trade, foreign investment and international knowledge diffusion, domestic production and productivity also depend on the R&D activities of other countries. The purpose of this paper is to empirically investigate the bilateral link between the U.S. and Japanese economies in terms of how R&D capital formation in one country affects the production structure, physical and R&D capital accumulation, and productivity growth in the other country.

We find that production processes become less labor intensive as international R&D spillovers grow. In the short-run, R&D intensity is complementary to the international spillover. This relationship persists in the long-run for the U.S., but the Japanese decrease their own R&D intensity. U.S. R&D capital accounts for 60% of Japanese total factor productivity growth, while Japanese R&D capital contributes 20% to U.S. productivity gains. International spillovers cause social rates of return to be about four times the private returns.

Jeffrey I. Bernstein
Department of Economics
Carleton University
Ottawa, Ontario K1S 5B6
CANADA
and NBER

Pierre Mohnen
Department of Economics
University of Quebec at Montreal
Montreal, Quebec H3C 3P8
CANADA

1. Introduction*

A wealth of evidence suggests that a country's production process and productivity growth depend on its current and past investments in R&D activities (see the surveys by Griliches [1988], and Nadiri [1993]). Moreover, with the growing importance of international trade in products and services, foreign direct investment, and international knowledge diffusion, a country's production structure and productivity growth depend, not only on the accumulation of its own R&D capital, but also on the R&D activities of other economies.[1] The purpose of this paper is to empirically investigate how U.S. R&D capital accumulation affects the production structure, physical and R&D capital formation, and productivity growth in the Japanese economy, and simultaneously how Japanese R&D investment affects these same elements in the U.S. economy.

There is a public good aspect to R&D capital accumulation. The benefits from R&D cannot be be completely appropriated by the R&D performers, and, inevitably, there are spillovers or externalities. R&D spillovers spur the diffusion of new knowledge, while they simultaneously create disincentives to undertake R&D investment. A number of recent empirical papers have shown the importance of domestic R&D spillovers in generating productivity gains and in affecting R&D capital accumulation (see the surveys by Griliches [1988], Cohen and Levin [1989], and Nadiri [1993]).

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R&D spillovers are not necessarily contained within national boundaries. International R&D spillovers are transmitted in a number of ways. Exports of goods and services, international alliances between firms, such as licensing agreements and joint ventures, foreign direct investment, international labor markets for scientists and engineers, and international communications, such as conferences, are some of the transmission mechanisms. It is important to emphasize that international transactions do not have to occur in order for spillovers to flow between nations. For example, Japanese automobile producers operating in the U.S. can perform reverse engineering on U.S. vehicles in the U.S. and transmit this information back to Japan. Thus the potential magnitude and extent of international spillovers can be quite pervasive.

In this paper we develop a bilateral model of production between the U.S. and Japanese economies (see Jorgenson and Nishimizu [1978], and Jorgenson, Sakuramoto, Yoshioka, and Kuroda [1990]). The significance of this approach is that production and R&D decisions for the U.S. and Japan are modeled simultaneously. International spillovers do not influence only productivity growth or production cost, but they simultaneously alter production structures, including decisions on R&D capital. Thus we estimate the effects of international R&D spillovers on production cost, traditional factor demands (such as the demand for labor), the demand for R&D capital, and productivity growth rates in each country.

We generalize the bilateral production model to account for adjustment costs associated with physical and R&D capital formation. Empirical evidence suggests that adjustment costs prevent producers from immediately attaining long-run equilibrium (see Morrison and Berndt [1981], Epstein and Yatchew [1985], Mohnen, Nadiri and Prucha [1986], and Bernstein and Nadiri [1989]). Producers adjust toward long-run equilibrium through successive short-run or temporary equilibria. Thus we are able to determine the bilateral effects on cost and production structure associated with international spillovers between the U.S. and Japanese economies in both the short and long-runs. Moreover, Berndt and Fuss [1986], Mohnen and Bernstein [1991], and Morrison [1992] have shown that it is important to account for deviations from long-run equilibrium in measuring productivity growth. Mistakenly assuming that producers are at their long-run desired capital stock levels (both for physical and R&D capital) can lead to significant biases in measured productivity growth rates and biases in accounting for the various determinants of productivity growth. In this paper we investigate the contribution to productivity growth from international spillovers within the context of adjustment costs for physical and R&D capital accumulation.

This paper is organized into a number of sections. The next section contains the specification of the model. Section 3 presents the estimation results, results from various hypothesis tests, and measures of adjustment costs. The international spillover effects in both the short and long-runs are described in section 4. The contribution of international spillovers to productivity growth and to the social rates of return are presented in section 5. In the last section we conclude the paper.

2. Model Specification

The model that we specify enables us to investigate the effects of Japanese R&D capital on the production structure in the U.S., and conversely the effects of U.S. R&D capital on Japanese production. Specifically, we want to determine the effects of one country's R&D capital on cost, factor demands, capital accumulation, and productivity growth in the other country. Production process in each country can be represented by,[2]

$$(1) \qquad y_t = F(v_t, K_{t-1}, \Delta K_t, S_{t-1})$$

where y is output, v is the n dimensional vector of variable factor demands, K is the m dimensional vector of quasi-fixed or capital factor demands, S is the o dimensional vector of R&D spillovers, which in a bilateral production model is the R&D capital from the other country, F is the production function.[3] In the production function the presence of $\Delta K = K_t - K_{t-1}$ signifies that there are adjustment costs associated with changes in the capital inputs.

The capital inputs accumulate according to,

$$(2) \qquad K_t = I_t + (I_m - \delta)K_{t-1}$$

where I is the vector of gross additions to the capital inputs, I_m is the m dimensional identity matrix, (as there are m capital inputs), and δ is the diagonal matrix of constant depreciation rates.

Production decisions in each country are determined under competitive conditions and according to the minimization of the expected discounted stream of costs. Thus,

$$(3) \qquad \min_{\{v_\tau, I_\tau\}_{\tau=0}^{\infty}} E(\Sigma_{\tau=0}^{\infty} \alpha(0,\tau)[w_\tau^T v_\tau + q_\tau^T I_\tau])$$

where E is the conditional expectations operator in the current period, α is the discount factor, w is the vector of exogenous variable factor prices, and q is the vector of exogenous capital acquisition prices. Now (3) is minimized subject to the production function, (equation (1)), the capital accumulation conditions, (equation (2)), and the expected stream of output, variable factor prices and capital acquisition prices. This problem can be solved in two stages. The first stage pertains to the determination of the variable factor demands, while the second stage relates to the demands for the capital inputs. Suppose for the moment that the capital inputs are given. In order to find the variable factor demands from (3), we minimize at each point in time $w^T v$ subject to the production function and conditional on the capital inputs. The variable factor demand functions which are obtained as the solution to this problem are considered the short-run production equilibrium conditions, because the capital inputs are fixed. Substituting the short-run equilibrium conditions into variable factor cost (that is $w^T v$) yields the variable cost function,

$$(4) \qquad c_t^v = C^v(w_t, y_t, K_{t-1}, \Delta K_t, S_{t-1})$$

where c^v is variable cost and C^v is the variable cost function, which is twice continuously differentiable, nondecreasing in w, y, and ΔK, nonincreasing in K, concave and homogeneous of degree one in w, convex in K and ΔK.

We specify the following functional form for the variable cost function,

$$(5) \qquad c_t^v = (\alpha^T w_t + .5 w_t^T \beta w_t W_t^{-1} + w_t^T \phi S_{t-1}) y_t^{\eta} + w_t^T \psi K_{t-1}$$
$$+ .5 K_{t-1}^T \xi K_{t-1} W_t / y_t^{\eta} + K_{t-1}^T \zeta S_{t-1} W_t + .5 \Delta K_t^T \mu \Delta K_t W_t / y_t^{\eta}$$

where $W = \gamma^T w$ is an index of variable factor prices, where the coefficient vector is known and defined by the particular index number.[4] The parameters are represented by the nx1 vector α, the nxn matrix β, the nxo matrix ϕ, the nxm matrix ψ, the mxm matrix ξ, the mxo matrix ζ, the mxm matrix μ, and the scalar η. The parameter matrices are assumed to be symmetric. This functional form is a simple extension of the one developed by Diewert and Wales [1987]. The extension involves the possibility of non-constant returns to scale (η is the inverse of the scale parameter) and adjustment costs (μ is the adjustment cost parameter matrix).[5] Adjustment costs are such that in the long run when there is no net investment, marginal adjustment costs are zero. The functional form incorporates the condition that the variable cost function is homogeneous of degree one in variable factor prices. The attractiveness of this functional form is that the concavity and convexity properties of the variable cost function can be imposed without restricting the flexibility of the function. In addition, under suitable expectations of the exogenous variables, closed form solutions can be obtained for the quasi-fixed factors.

The demands for the variable factors are retrieved from the variable cost function by applying Shephard's Lemma (see Diewert [1982]). Thus with $v_t = \nabla_w C^V(w_t, y_t, K_{t-1}, \Delta K_t, S_{t-1})$, and using (5),

$$(6) \qquad v_t = (\alpha + \beta^T w_t W_t^{-1} - .5 w_t^T \beta w_t W_t^{-2} \gamma + \phi^T S_{t-1}) y_t^{\eta} + \psi^T K_{t-1}$$

$$+ (.5 K_{t-1}^T \xi K_{t-1} / y_t^{\eta} + K_{t-1}^T \zeta S_{t-1} + .5 \Delta K_t^T \mu \Delta K_t / y_t^{\eta}) \gamma .$$

The variable factor demands depend on the variable factor prices, output, the capital inputs, net investment in the capital inputs and the R&D spillovers.

In order to determine the demands for the capital inputs, substitute the right side of (5) into (3) for $w^T v$ and maximize (3) subject to the capital accumulation equations (given as equation set (2)). Assuming that relative variable factor prices (w/W), output, R&D spillovers and the real discount rate ($\alpha(t,t+1) = (1+r)^{-1}$) are not expected to change, then the demands for the capital inputs are given by,[6]

$$(7) \qquad K_t = M K_t^e + (I_m - M) K_{t-1}$$

where M is the adjustment coefficient matrix, and the long-run demands for the capital inputs are $K_t^e = -\xi^{-1}A_t$, where $A_t = [\psi w_t/W_t + \zeta S_{t-1} + w_t^k/W_t]y_t^{\eta}$, and $w^k = (rI_m + \delta)q$ is the vector of rental rates for the capital inputs.

The matrix of adjustment coefficients must satisfy the following matrix equation,

$$(8) \qquad \mu M^2 + (\xi + r\mu)M - \xi = 0.$$

In general, we cannot solve for M in terms of ξ and μ. However, as shown by Epstein and Yatchew [1985], we are able to solve for ξ in terms of μ and M. Define $B = -\mu M$ and $C = -M\xi^{-1}$, where B and C are symmetric matrices. Thus, using (8), $C = \mu^{-1} + (1 + r)(B - r\mu)^{-1}$, and the demands for the capital inputs can be written as,

$$(9) \qquad K_t = CA_t + (I_m + \mu^{-1}B)K_{t-1}.$$

The demands for the capital inputs are written in terms of the parameter matrices B and μ. Notice that the adjustment coefficient matrix can be obtained from these parameter matrices, as $M = -\mu^{-1}B$. The demands for the capital inputs depend on the lagged values of these inputs, and through the A matrix, the demands also depend on variable factor prices, the rental rates, output quantity, and the R&D spillovers.[7]

The set of equations to be estimated consists of (6) and (9), which relate to the demands for the factors of production. Our emphasis in this paper is on the effects that international R&D spillovers have on production structure and productivity growth. We see that this framework enables us to investigate the impact of international R&D spillovers on factor demands in the short and long runs, as well on the decomposition of productivity growth.

3. Estimation Results

The data used to estimate the model relate to a common set of industries and time period for the United States and Japan. There are eleven industries. These are Food and and Kindred Products, Paper and Allied Products, Chemicals and Allied Products, Petroleum and Coal Products, Stone Clay and Glass, Primary Metals, Fabricated Metals, Non-electrical Machinery, Electrical Products, Transportation Equipment, and Scientific Instruments. The sample period is 1962-1988. The non-R&D data are described in detail in Denny, Bernstein, Fuss, Waverman and Nakamura [1992].[8] The industries for each country are aggregated by Fisher indexes (see Diewert [1989]) into a single sector. We refer to this sector as the R&D intensive sector as 90% of all manufacturing R&D investment is performed here.[9] The industries are aggregated into broad R&D sectors because we are interested in the effects of international spillovers. We want to abstract from the spillovers that exist between the industries within a country.[10]

The data consist of prices and quantities for two variable factors, labor and intermediate; two capital inputs, physical and R&D, output quantity, and R&D spillover, which is the R&D capital of the foreign R&D intensive sector. The data for the Japanese and U.S. R&D intensive sectors are treated as separate sets of observations. These observations are assumed to be generated by an econometric model with distinct first order parameters (represented by the α vector), distinct R&D spillover parameters (represented by the ϕ, and ζ matrices), distinct scale parameter (represented by the inverse of η), and the remaining second order parameters are common. In this model differences in the technology across countries at a point in time are reflected in differences in the α and η parameters. Differences in the technology over time between the countries are represented by differences in the spillover parameters (that is by the ϕ and ζ matrices).

Unobservable stochastic disturbances are added to equation sets (6), and (9). These disturbances reflect random elements in the production process not reflected in the variable cost function, and errors of implementation of the production plans. The disturbances have zero expected value and positive definite covariance matrix.[11]

Equation sets (6) and (9) were jointly estimated using the nonlinear Maximum Likelihood Estimator. The first set of estimates produced scale estimates of 1.004 and 1.021 for the U.S. and Japan respectively. In this case the log of the likelihood function increased by only 1.329 over the constant returns to scale model. Thus we could not reject constant returns to scale for both the U.S. and Japanese R&D intensive sectors.[12] We then proceeded to estimate the model under constant returns to scale. In addition, we generalized the flexible accelerator in the following way,

$$N = M + \theta d = -\mu^{-1}B + \theta d \tag{10}$$

where θ is a two dimensional symmetric parameter matrix, and d is a dummy variable that takes the value of 1 in short-run equilibrium and 0 in long-run equilibrium.[13] Recall that the M matrix is the adjustment matrix (see equations (7) and (9)). If θ is zero then the model is consistent with the flexible accelerator. Equation sets (6) and (9) were estimated under the hypotheses that $\theta = 0$ and $\theta \neq 0$. Under the null hypothesis the log of the likelihood function was 484.474 and under the alternative hypothesis the value was 534.223. Therefore we reject the simple flexible accelerator model and adopt the generalized form. These estimates are presented in table 1.[14] In table 1 we see from the squared correlation coefficients, that the model fits the data quite well.[15] We also estimated the model with only first order and spillover parameters. In other words we set $\beta_{ii} = \psi_{ij} = \xi_{kj} = \mu_{kj} = \theta_{kj} = 0$, $i = 1,m$, $k,j = p,r$. In this situation the log of the likelihood function was 483.219. Thus we reject the absence of second order parameters in the estimation model. The model was also estimated when the spillover parameters were set to zero. We set $\phi_{is} = \zeta_{is} = 0$, $i = p,r$. In this case the log of the likelihood function was 521.297, and so we reject the model without R&D spillovers.

In order to see if the U.S. and Japanese sectors are in long-run equilibrium, the model was estimated under the condition that $\mu_{ij} = 0$, $i,j = p,r$. With the three adjustment parameters (since $\mu_{ij} = \mu_{ji}$) set to zero the

Table 1. Estimation Results

Parameter	Estimate	Standard Error
α_{l}^{u}	0.1079	0.7875
α_{l}^{j}	2.4569	1.0472
α_{m}^{u}	1.3800	0.7272
α_{m}^{j}	0.9070	0.2164
β_{ll}	-0.9150	0.4449
ϕ_{ls}^{u}	-0.8010E-06	0.1917E-05
ϕ_{ls}^{j}	-0.4233E-05	0.1266E-05
ψ_{lp}	-2.1029	1.4615
ψ_{lr}	3.7565	3.0884
ψ_{mp}	-4.8072	4.4812
ψ_{mr}	2.6887	4.5011
b_{pp}	-68.0859	54.0610
b_{pr}	58.1626	88.1947
b_{rr}	-104.4000	101.0550
ζ_{ps}^{u}	0.2233E-04	0.2269E-04
ζ_{ps}^{j}	0.8489E-05	0.8669E-05
ζ_{rs}^{u}	-0.2835E-04	0.2868E-04
ζ_{rs}^{j}	-0.8282E-05	0.9111E-05
μ_{pp}^{u}	323.3500	235.9560

Parameter	Estimate	Standard Error
μ^{j}_{pp}	314.2790	442.9070
μ^{u}_{rr}	716.9660	980.8800
μ^{j}_{rr}	763.8890	685.7400
ϑ_{pp}	0.1575	0.0836
ϑ_{rr}	0.3561	0.3579
ϑ_{pr}	-0.1811	0.1544

Log of the Likelihood 534.223

Squared Correlation of Actual and Fitted

Labor demand	0.9693
Material demand	0.9402
Phy. Capital demand	0.9988
R & D Capital demand	0.9997

Table 2. Adjustment Coefficients

	Physical Capital		R&D Capital	
	U.S.	Japan	U.S.	Japan
Physical Capital	0.211	0.217	-0.180	-0.185
R&D Capital	-0.081	-0.076	0.146	0.137

log of the likelihood was 409.073. Thus we reject long-run equilibrium for the R&D intensive sectors of the Japanese and U.S. economies. Indeed, we can calculate the speeds of adjustment towards long-run equilibrium from the matrix $M = -\mu^{-1}B$. The speeds of adjustment are presented in table 2. This table shows us that the own adjustment speed for physical capital is 45% faster than for R&D capital in the U.S., while in Japan, physical capital adjusts 58% faster than R&D capital. Ignoring the cross adjustment coefficients for the moment, we find in the U.S. that around 21% of the adjustment for physical capital occurs in the first year. In this same time period only about 15% of the gap between long and short-run R&D capital stock closes. For Japan the corresponding speeds are 22% and 14%. The results on the relative magnitudes of the own adjustment speeds are similar to Mohnen, Nadiri and Prucha [1986], for U.S and Japanese manufacturing sectors, Bernstein and Nadiri [1989] for U.S. firms, and Nadiri and Prucha [1990] for U.S., and Japanese electrical products industries. However, we find that the own adjustment speeds for the R&D intensive sectors of the two economies are faster than for the manufacturing sector as a whole.

The cross adjustment coefficients in table 2 are negative. This means that physical and R&D capital are adjustment complements. Thus when the long-run demand for physical capital exceeds the short-run demand the adjustment of R&D capital decelerates. This same process occurs when the roles of the two capital stocks are reversed. An excess demand for physical capital slows the adjustment process of R&D capital by around 18% in a single year in the U.S. and in Japan. In addition, an excess demand for R&D capital slows the physical capital adjustment by 8% in one year in the U.S. and Japan. In general, we do not find adjustment speeds too dissimilar between the U.S. and Japanese R&D intensive sectors.

4. Spillover Effects

In this section we consider the effects of international R&D spillovers on the structure of production. We have seen that the estimation model without international R&D spillovers can be rejected. Thus we want to calculate the effects of the spillover on variable cost and factor demands. In particular, we calculate both the short and long-run effects that Japanese R&D capital exerts on the labor-output, intermediate input-output, physical capital-output, and R&D capital-output ratios for the U.S. R&D intensive sector. Similarly, we compute the effects for the Japanese R&D intensive sector based on changes in the U.S. R&D capital.

To determine the short-run spillover effects, differentiate the capital input demand equations (equation set (9)) with respect to the spillover variable,

$$\partial(K_t/y_t)/\partial S_{t-1} = C\zeta. \tag{11}$$

Since capital inputs affect the short-run demand for the variable factors through the capital-output ratio and adjustment costs, differentiating equation set (6) with respect to the spillover yields,

$$(12)\quad \partial(v_t/y_t)/\partial s_{t-1} = \phi + \gamma(K_{t-1}/y_t)^T\zeta + \gamma(\Delta K_t/y_t)^T\mu(\partial(K_t/y_t)/\partial s_{t-1}).$$

Equation (12) shows that there are three effects of R&D spillover on the variable factor demands. There is the direct effect through ϕ and the indirect effects associated with the capital inputs through ζ, and with net investments through μ.

From the specification of the average variable cost function (which is equation (5)), we see that it is affected by R&D spillovers. Differentiating equation (5) with respect to the R&D spillover leads to,

$$(13)\quad \partial(c_t^v/y_t)/\partial s_{t-1} = w_t^T\phi + (K_{t-1}/y_t)^T\zeta w_t + (\Delta K_t/y_t)^T\mu(\partial(K_t/y_t)/\partial s_{t-1})w_t.$$

There are three effects of the international R&D spillover on unit variable cost. The first is the direct unit cost-reducing effect which arises from ϕ. From table 1 we see that this effect is indeed negative (as $\phi_{1s}<0$). The remaining two effects operate through the capital intensities and adjustment costs.

The elasticity conversions of equations (11), (12), and (13) are presented in table 3. From this table we see that in the short run a 1 percent increase in the U.S. R&D capital decreases Japanese average variable cost by 0.63%. This is the direct effect on average variable cost holding fixed the factor intensities. Since an increase in R&D spillovers represent technological change, the direct effect on average variable cost defines a

Table 3: Short-Run Spillover Effects

	United States		Japan	
	Mean	Std. Dev.	Mean	Std. Dev.
Direct Avg. Var. Cost	-0.0538	0.0273	-0.6334	0.4493
Average Variable Cost	0.2410	0.1857	-0.4260	0.3583
Labor / Output	-0.0144	0.0556	-3.5455	1.4255
Inter. Input / Output	0.3158	0.2051	0.3959	0.1385
Phy. Cap. / Output	-0.0150	0.0085	-0.1301	0.0235
R&D Cap./ Output	0.0255	0.0154	0.0526	0.0068

measure of the rate of technological change. Thus there are technological gains for Japan from international spillovers. The U.S. also benefits from international spillovers. Japanese R&D capital directly reduces U.S. average variable cost, but the effect is about twelve times smaller than the spillover effect generated for the Japanese R&D intensive sector.

From table 3 we see that international R&D spillovers reduce the labor-output, and physical capital-output ratios for both the U.S. and Japanese sectors. In the U.S., labor and physical capital output ratios decline by 0.02%, but in Japan these ratios decrease by 3.5% and 0.13% respectively. The effects from U.S. R&D capital are significantly greater than the effects arising from the Japanese generated spillover. Moreover, Japan's labor intensity dramatically declines as a result of U.S. R&D investment. International spillovers alter Japan's production process such that output is produced more intensively using intermediate inputs at the expense of physical capital and especially labor.[16]

It is interesting to note that the R&D intensities increase for both countries a result of the spillovers. As we observe from table 3, international spillovers cause the Japanese R&D intensive sector to increase its R&D intensity by more than twice the effect found in the U.S.. In a sense own R&D intensity is complementary to new knowledge obtained from foreign sources. Cohen and Levinthal [1989] have emphasized the complementarity between R&D activities and domestic spillovers. In this paper we see that this relationship also exists between international spillovers and R&D capital.

The long-run spillover effects are are derived by noting that the long-run capital input demands are given by $K_t^e = \xi^{-1} A_t$, and so,[17]

(14) $$\partial(K_t^e/y_t)/\partial S_{t-1} = \xi^{-1}\eta.$$

To obtain the long-run spillover effects on average variable cost and the variable input-output ratios, in equation set (5) and (6) set $\Delta K = 0$, and substitute K_t^e for K_{t-1}. Thus we get,

(15) $$\partial(v_t^e/y_t)/\partial S_{t-1} = \phi + \psi\partial(K_t^e/y_t)/\partial S_{t-1} + \gamma(K_t^e/y_t)^T\xi\partial(K_t^e/y_t)/\partial S_{t-1} + \gamma(K_t^e)^T\eta + \gamma(\eta S_{t-1})^T\partial(K_t^e/y_t)/\partial S_{t-1},$$

(16) $$\partial(c_t^v/y_t)/\partial S_{t-1} = w_t^T\phi + w_t^T\psi\partial(K_t^e/y_t)/\partial S_{t-1} + W_t(K_t^e/y_t)^T\xi\partial(K_t^e/y_t)/\partial S_{t-1} + W_t(K_t^e)^T\eta + W_t(\eta S_{t-1})^T\partial(K_t^e/y_t)/\partial S_{t-1}.$$

The long-run spillover effects are presented in elasticity form in table 4. We see that, as in the short run, the Japanese results are relatively more elastic. Indeed for Japan in the long-run a 1% increase in U.S. R&D capital leads to a 1% decrease in average variable cost. This is the direct effect of the spillover on unit variable cost before Japan alters its production process in light of the new knowledge it obtains via the international spillover. An interesting feature of the long-run results is that as new knowledge is transmitted from the U.S. to Japan the latter reduces its own R&D intensity. The international spillover enables Japan to rely less on its own R&D capital per unit of output produced. This is not

Table 4. Long-Run Spillover Effects

	United States		Japan	
	Mean	**Std. Dev.**	**Mean**	**Std. Dev.**
Direct Avg. Var. Cost	-0.0693	0.0390	-1.0569	0.4395
Average Variable Cost	0.1356	0.0396	-0.4300	0.5635
Labor / Output	-0.7623	0.3379	-2.0581	0.8722
Materials / Output	-0.0094	0.0971	1.2088	0.5077
Phy. Cap. / Output	0.0211	0.0134	-0.5461	0.2156
R&D Cap. / Output	0.2418	0.1255	-0.2607	0.1035

the case for the U.S., in the long-run, as in the short-run, R&D intensity increases with the spillover from Japan. The U.S. does not substitute its own R&D capital per unit of output for the international spillover.

5. Productivity Growth and Social Returns

Total factor productivity (TFP) growth is a measure of the dynamic efficiency of a producer.[18] In this section of the paper we want to measure and decompose TFP growth for the U.S. and Japanese R&D intensive sectors. In particular, we want to determine the contribution of R&D spillovers to TFP growth rates.

By definition the traditional measure of TFP growth is the difference between output and input growth rates. In our context, inputs are defined by labor, physical capital, intermediate inputs, and R&D capital. Hence TFP growth can be measured in discrete time as,

$$(17)\quad TFPG(t,s) = (y_t - y_s)/y_m - s_{vm}^T(v_t - v_s)/v_m - s_{km}^T(K_t - K_s)/K_m,$$

where the subscript t represents the current period, and s represents the past period, the subscript m designates the mean value of a variable (for example $y_m = (y_t + y_s)/2$), s_v is the vector of variable factor cost shares, s_k is the capital cost shares, and the cost shares are defined in terms of the cost of the variable and quasi-fixed factors.[19]

We are able to decompose TFP growth rates by using the estimated variable cost function. Since the variable cost function is in the family of second order quadratic forms whose second order parameters do not change over time, then TFP can be decomposed into (see Denny and Fuss [1983]),[20]

$$
\begin{aligned}
(18) \qquad c^v_t - c^v_s = .5[&\Sigma_{i=1}^{n}(v_{it} + v_{is})(w_{it} - w_{is}) \\
&+ ((\partial c^v/\partial y)_t + (\partial c^v/\partial y)_s)(y_t - y_s) \\
&+ \Sigma_{k=1}^{m}((\partial c^v/\partial K_k)_t + (\partial c^v/\partial K_k)_s)(K_{kt} - K_{ks}) \\
&+ \Sigma_{k=1}^{m}((\partial c^v/\partial \Delta K_k)_t + (\partial c^v/\partial \Delta K_k)_s)(\Delta K_{kt} - \Delta K_{ks}) \\
&+ \Sigma_{j=1}^{o}((\partial c^v/\partial S_j)_t + (\partial c^v/\partial S_j)_s)(S_{jt} - S_{js})].
\end{aligned}
$$

Equation (18) shows the difference in variable cost between two time periods. The difference is attributable to the variable factor prices, output quantity, capital stocks, net investment flows, and R&D spillovers. Variable cost depends on these variables. In addition, by definition of variable cost, the change over two periods is given by, $c^v_t - c^v_s = \Sigma_{i=1}^{n}(w_{is}(v_{it} - v_{is}) + v_{it}(w_{it} - w_{is}))$. Using this result with (17), and (18), yields,

$$
\begin{aligned}
(19) \quad TFPG(t,s) = ((y_t - y_s)/y_m)[1 &- (\partial c^v/\partial y)_m(y_m/c^v_m)(c^v_m/c_m)) \\
&- (c^v_m/c_m)\Sigma_{k=1}^{m}[(\partial c^v/\partial K_k)_m + w_{km}](K_{km}/c^v_m)(K_{kt} - K_{ks})/K_{km} \\
&- \Sigma_{k=1}^{m}[(\partial c^v/\partial \Delta K_k)_m(\Delta K_{km}/c_m)(\Delta K_{kt} - \Delta K_{ks})/\Delta K_{km}] \\
&- \Sigma_{j=1}^{o}(\partial c^v/\partial S_j)_m(S_{jm}/c_m)(S_{jt} - S_{js})/S_{jm}.
\end{aligned}
$$

The decomposition of TFP growth, as shown by the right side of equation (19), consists of four elements. The first element is the short-run scale effect, where $(\partial c^v/\partial y)_m(y_m/c^v_m)$ can be defined as the short-run cost flexibility or the inverse of the short-run degree of returns to scale (evaluated at the means of the variables). The second element relates to the capital adjustment effects, which arise because the rental rate on each capital input does not equal the cost reduction from this factor of production. The third element consists of the adjustment cost effects associated with both physical and R&D capital. The last element is the R&D spillover effect.

The spillover effect can be further decomposed into two elements. These two facets can be obtained from equation (13) where we observed that there is both a direct and indirect effect of the spillover on variable cost. Noting that $\partial c^v/\partial S = y\partial(c^v/y)/\partial S$, we can substitute the right side of equation (13) into the last term on the right side of equation (19). The direct effect, which is defined as the effect on variable cost when all input-output ratios are held fixed, can be considered the traditional technological change effect on TFP growth. Notice that although the spillover effect is exogenous to the spillover receiver, it is not exogenous in the bilateral model of production, since it is the R&D capital of the spillover source. The indirect spillover effect on productivity growth represents the impact on factor intensities from the new knowledge obtained from the foreign country.

TFP growth and decomposition for the U.S. and Japanese R&D intensive sectors are presented in table 5. Japanese TFP growth generally exceeds the rate obtained for the U.S. R&D intensive sector. Differences in TFP growth are not that great until 1974. However, from the mid seventies until the mid eighties the Japanese R&D intensive sector significantly out performs the U.S. sector. The main source of TFP gains for both countries arises from the marginal profitability of capital accumulation (both physical and R&D capital). Capital accumulation is profitable because the marginal benefit of physical and R&D capital (as represented by their respective variable cost reductions) exceeds their rental rates. This differential creates the incentive for capital expansion.

The second major source of TFP improvement occurs as a result of the direct international spillover effect, or in other words the technological change effect. International R&D spillovers are a consistent source of TFP gains for both countries over the sample period, as they generate direct variable cost reductions. In addition, spillovers generally increase the demands for the variable inputs. This, in turn, causes variable cost to rise, and productivity growth to fall. Thus the indirect international spillover effect reduces TFP growth.

From table 5, we observe that the gains from the direct spillover effect are greater for Japan compared to the U.S.. Moreover, the losses associated with the indirect spillover effect are relatively smaller for the Japanese R&D intensive sector. Abstracting from the indirect spillover effect, the direct effect from Japanese R&D capital contributes about 20% to U.S. productivity growth over the two decades from the mid sixties to the mid eighties. The direct contribution of U.S. R&D capital to Japanese productivity growth is substantially greater than the impact of Japanese R&D capital on U.S. TFP growth. Over the same time period, the U.S. effect

Table 5. Decomposition of Average Annual TFP Growth Rates

	TFPG	Scale	Capital	Adjust.	Dirspil.	Indspil.
			percent			
United States						
1963-1967	0.953	0.802	4.353	-3.861	0.175	-0.516
1968-1973	2.413	0.369	2.556	1.081	0.534	-2.127
1974-1979	-0.396	-0.314	1.956	-0.180	0.405	-2.263
1980-1985	-2.413	0.116	0.809	0.127	0.632	-4.097
1963-1985	0.104	0.219	2.334	-0.571	0.448	-2.326
Japan						
1963-1967	1.749	-0.144	3.997	-1.685	1.136	-1.555
1968-1973	2.289	0.640	3.239	-1.830	1.125	-0.885
1974-1979	2.279	0.312	0.646	0.936	1.122	-0.737
1980-1985	1.394	0.000	1.118	-2.243	3.967	-1.448
1963-1985	1.935	0.217	2.174	-1.185	1.868	-1.139

accounts for around 60% of Japanese TFP growth in its R&D intensive sector.

The social rates of return to R&D capital equal the private rates of return plus the returns associated with the international spillovers.[21] These latter returns can be calculated by considering a situation where the international spillovers have been internalized. In this regard we define the joint U.S.-Japan expected discounted flow of funds,

$$\Omega_0 = \Sigma_{j=1}^{2} E^j \Sigma_{\tau=0}^{\infty} \alpha^j(0,\tau)[C^{vj}(w_\tau^j, y_\tau^j, K_{\tau-1}^j, \Delta K_\tau^j, S_{\tau-1}^j) + q_\tau^j(K_\tau^j - (I_m - \delta^j)K_{\tau-1}^j)]. \tag{20}$$

The superscript j refers to the country.

Consider the right side of equation (20) to be evaluated at the equilibrium input-output ratios for each country. In equilibrium, expected discounted cost for each country is at a minimum. However, joint expected discounted cost is not minimized relative to the case where the international spillovers are internalized. With the internalization of the R&D spillovers, there is additional profit (through cost reductions) to be earned from each of the R&D capital stocks. The additional profit is the reduction in joint cost. Using equation (5), the reduction in joint cost in equilibrium in period t+1 from an increase in the ith country's R&D capital is,

$$\partial\Omega_{t+1}/\partial S_t^j = [w_{t+1}^{jT}\phi^j + (K_t/y_{t+1})^{jT}\zeta^j W_{t+1}^j]y_{t+1}^j. \tag{21}$$

Recall that the spillover to country j is the ith country's R&D capital. Equation (21) shows the wedge between the social and private rates of return evaluated in equilibrium.

Next we need the private rate of return to R&D capital for each country. This return is obtained from the first order condition for R&D capital as part of the problem defined by (3). The private return is the discount rate (that is the opportunity cost of funds) plus the marginal adjustment costs per dollar of capital stock. Defining ρ^{j}_{rt} to be the private rate of return of R&D capital in period t for country j, we have,[22]

$$(22) \qquad \rho^{j}_{rt} = r^{j} + \Sigma_{k=p}^{r}\mu^{j}_{rk}\Delta K^{j}_{kt}/q^{j}_{rt}.$$

Thus the social rate of return to R&D capital for country j is,

$$(23) \qquad \gamma^{j}_{rt} = \rho^{j}_{rt} + (\partial\Omega_{t+1}/\partial S^{j}_{t})/q^{j}_{rt}.$$

Using equation (22), the sample mean private rates of return to R&D capital for the U.S. and Japanese R&D intensive sectors are respectively 0.169 and 0.176. The estimates for the private returns are quite similar and are consistent with those obtained in other studies (see for example Bernstein and Nadiri [1988] for the U.S. and Goto and Suzuki [1989] for Japan). The sample mean of the wedge between the social and private returns that accounts for the international spillovers between the U.S. and Japan (this is the second term on the right side of (23)) is 0.509 for the U.S., and 0.395 for Japan. Therefore the social rate of return for U.S. R&D capital is 0.678 or more than 300% greater than the private rate of return. For the Japanese R&D intensive sector the social rate of return is 0.571 or about 225% greater than the private return.

The estimates of the social returns associated with the international spillovers between the U.S. and Japan have not been previously calculated. However, they are not out of line with the estimates associated with domestic R&D spillovers (see for example the survey by Nadiri [1993]. It appears that international spillovers are potentially as important as domestic spillovers.

6. Conclusion

The empirical results in this paper show that for the U.S. and Japanese R&D intensive sectors domestic production cost, traditional factor intensities, and R&D capital intensity are affected by international R&D spillovers between the two countries. These findings exist in both the short and long-runs. However, there are important differences in the results across runs and across countries. Short-run domestic R&D intensity is complementary to the international spillover. In the U.S. a 1% increase in the international spillover causes R&D intensity to rise by 0.02%, while for Japan the effect is twice the U.S. elasticity. The complementarity persists and becomes stronger for the U.S., in the long-run Japan substitutes U.S. R&D capital for its own and thereby reduces its R&D intensity.

The most dramatic difference between the two countries has to do with labor intensity. Japan reduces its labor intensity by 3.5% in response to a 1% increase in the international spillover from the U.S.. The corresponding elasticity for the U.S. is only 0.01%. The Japanese R&D intensive sector substantially increases its knowledge intensity as the international spillover from the U.S. grows. In this situation we find that empirically it is important to distinguish between short and long-run equilibrium specifications, and to distinguish between the technologies in the U.S. and Japan when investigating the effects of international spillovers.

International R&D spillovers directly contribute to productivity growth in both countries. International spillovers from the U.S. account for about 60% of Japanese productivity growth. The contribution from Japan to the U.S. is smaller, but nevertheless not inconsequential, as the magnitude is 20%. The existence of international spillovers imply that social rates of return to R&D capital exceed private returns. We estimated that the private rates of return to R&D capital are around 17% in both countries, while the social returns are three and a half to four times greater than the private return.

Footnotes

[1] For a theoretical development of the international role of R&D capital accumulation see Ethier [1982], and Grossman and Helpman [1991].

[2] For simplicity, we do not introduce country specific notation. See Diewert [1982] for the properties relating to production functions.

[3] See Griliches [1979] for a discussion on the issues relating to R&D spillovers in the production function. Bernstein and Nadiri [1989] have applied the production approach to the analysis of domestic intraindustry and interindustry spillovers.

[4] W is defined to be a Laspeyres price index of the variable factors of production. Thus the γ vector of coefficients consists of the variable factor cost shares in the period of normalization, which is 1985.

[5] Although there is the possibility of non-constant returns to scale, the degree of returns to scale is assumed to be exogenous.

[6] We can also solve the model when expectations are based on autoregressive processes, or when there is perfect foresight. In addition, if the capital inputs are immediately productive then we just need to form expectations on real output (y/W).

[7] It should also be noted that the demands for the variable factors are also affected by the reparameterization of the solution to the capital inputs, since the parameter matrices μ and ξ appear in these demand equations.

[8] The base period for the data in this paper is 1985. Thus we adjusted all U.S. price indexes to be one in 1985 and we adjusted the purchasing power parities (PPP), obtained from Jorgenson and Kuroda [1990], to be indexed in 1985. We also avoided double counting by subtracting the R&D expenditure components from costs of labor, physical capital, and intermediate inputs. The R&D capital stock is developed by accumulating deflated R&D expenditures, assuming a depreciation rate of 10% (see Nadiri and Prucha [1993]). Initial stocks were calculated by grossing up initial deflated expenditures by the depreciation rate plus the growth rate of physical capital.

[9] These industries also account for around 80% of manufacturing output and employment in each country.

10 See Bernstein and Nadiri [1988] for results on U.S. interindustry spillovers, and Goto and Suzuki [1989] for results on Japanese industries.

11 In the estimation of equation sets (6), and (9), we can impose the conditions that the variable cost function must be concave in the variable factor prices and convex in the capital inputs and net investment. These conditions result in the following parameter restrictions, $\beta = -DD^T$, $\xi = EE^T$ and $\mu = GG^T$, where D, E and G are lower triangular matrices. We do not impose these conditions because the estimates turn out to satisfy them. In order to identify the parameters we impose the restriction that $\beta i = 0_m$, where i is the unity vector.

12 The definition of returns to scale is inclusive of the R&D capital input and adjustment costs in both physical and R&D capital inputs. There are no previous estimates of returns to scale in these sectors, as a whole, although Nadiri and Prucha [1990] found slightly increasing returns to scale in the U.S. and Japanese electrical products industries.

13 The dummy variable is associated with the parameter matrix ϑ, because the test regarding the flexible accelerator can only be conducted in a short-run equilibrium.

14 Under constant returns to scale the model was estimated in ratio form. In other words the endogenous variables are input-output ratios.

15 The correlation coefficients are between observed and predicted endogenous variables, where the predicted values are computed from the reduced form estimated equations. In addition, we see from table 1 that without imposing the curvature conditions that the variable cost function is concave in the variable factor prices as $\beta_{11}<0$, the function is convex in the capital inputs as $b_{ii}<0$, $i = p, r$, and $b_{pp}b_{rr} - b_{pr}^2>0$ (recall that the B matrix is negatively related to the ξ matrix from equations (7) and (9)), and the function is convex in net investments as $\mu_{ii}>0$, $i = p, r$, and $\mu_{pp}\mu_{rr} - \mu_{pr}^2>0$.

16 The directional changes found for international spillovers are similar to those obtained from domestic spillover studies in the U.S. and Japan (see Bernstein and Nadiri [1988] and Goto and Suzuki [1989]).

17 See equation (7), and the discussion that follows.

[18] See Denny and Fuss [1983], and Diewert [1989] for discussions of the different measures and interpretations of productivity growth.

[19] All current period capital stocks refer to the beginning of period quantities which are lagged one period.

[20] A unit variable cost function was estimated. However, this does not pose a problem for the TFP decomposition, since $\partial c^v/\partial z = y\partial(c^v/y)/\partial z + \delta_z$, $\delta_z = c^v/y$ if $z = y$, and 0 otherwise.

[21] The private rates of return relate to the R&D intensive sector in each country. In addition, any intrasectoral spillovers have been internalized. Since we are focusing on international spillovers, domestic spillovers between the R&D intensive sector and other sectors of the economy of a country are assumed to be inconsequential. This appears to be reasonable since about 90% of R&D investment in both the U.S. and Japanese economies are performed within the R&D intensive sector.

[22] The rate of return for R&D capital is found from the Euler equation by equating the expected marginal benefit to the expected marginal cost. The former is the expected future cost reductions (including adjustment cost savings) net of depreciation per dollar of capital stock. The expected marginal cost is the discount rate plus marginal adjustment costs per dollar of capital stock. The rates of return on R&D capital are defined as before tax returns.

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