INTERNATIONAL R&D SPILLOVERS AND OECD ECONOMIC GROWTH

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This paper quantifies the cross-national spillover effects of government and private investment in research and development (R&D), using a panel data set of ten OECD countries. The results show that domestic private research is a significant determinant of both domestic and foreign productivity growth, and that foreign government research stimulates domestic private research. These findings are significant in that they provide empirical support for arguments in favor of international economic policy coordination, particularly in the area of international science and technology.

I. INTRODUCTION

This paper searches for evidence of *knowledge spillovers* operating at the global level. Using research spillovers as a measure of knowledge flows, it studies the extent to which national research and development (R&D) investments generate global externalities—that is, affect productivity growth and R&D investments in other countries. Should they exist, international knowledge spillovers would have important welfare implications for the international coordination of economic policy.

Yet international knowledge spillovers have not been the focus of much attention in the literature on international economic policy coordination.[1] Instead existing work has primarily focused on "price" variables as the means by which the effects of domestic government policies spill over to other countries.[2] For example, it is argued that fiscal policies of large countries impose externalities on other countries by altering world prices, such as the terms of trade, exchange rate, or world interest rate. Avoiding or minimizing these external effects is shown to be a basis for policy coordination. However, as Scitovsky [1954] points out, externalities are of two kinds: pecuniary and technological. Pecuniary externalities work through the price system, whether through the prices of factor inputs or of outputs. When markets are competitive, pecuniary externalities are simply the outcomes of normal marketplace interactions. They do not constitute sufficient grounds for social intervention. Price changes effect distributional changes, but do not by themselves reflect market failure—indeed, they reflect the market system at work! In contrast, an efficiency-based case for public policy intervention can be made when "technological externalities" arise, as when the production activities of an agent affect the production of another agent other than by influencing the latter's input costs or output prices. In the presence of technological externalities the private market will generally not lead to socially optimal outcomes.

In an open-economy context the significance of distinguishing between these two types of externalities is that when government policies generate technologi-

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1. A seminal reference is Buiter and Marston [1985].

2. See for example Devereux [1987], Frenkel and Razin [1987], and Ihori [1987].

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cal externalities, international fiscal coordination is desirable from an allocative efficiency point of view, provided that global public intervention itself does not introduce further distortions.[3] With research spillovers operating at the global level, the international market system tends not to yield a globally efficient and equitable allocation of resources, as some beneficiaries of research in the world neither bear the cost of R&D nor compensate (through the market system) foreign agents that fund or perform R&D. In this instance, there is scope for intergovernmental intervention to improve the provision of internationally enjoyed public goods (provided the same problems which beset the international market mechanism do not beset the international public mechanism). The gains from international economic policy coordination will therefore be more significant when international technological spillovers are accounted for than when only pecuniary sources of interdependence are taken into account.

These issues also have relevance for the recent literature on endogenous growth[4] in that several theoretical growth models have *assumed* the existence of knowledge spillovers that go beyond national (geographical) boundaries. Yet there have been few empirical studies on whether they do exist. Recently, Lichtenberg [1992] has studied international economic convergence and R&D spillovers using a cross-country data set and found that spillovers are not complete or instantaneous. I use a smaller sample of countries in a panel data framework, which provide an alternative perspective. Coe and Helpman [1993] have also studied international knowledge spillovers in a panel data framework but do not distinguish between the roles of public and private R&D, as I do. Since governments tend to fund nearly half their nations' research, it is important to consider how different sectors generate research spillovers. Another study of foreign R&D spillovers is Mohnen [1990], which focuses on the impact of foreign industrial research on the productivity of Canadian manufacturing. I use much more aggregated data in order to address the issue of international spillovers from a *global* market perspective. For this reason, the aggregate data should serve as a good first start to see if one can capture international spillovers at a macroeconomic level, before pursuing the microeconomic details behind cross-national spillovers.

Using OECD data in a growth-accounting framework, I look for evidence of technological externalities based on whether one country's research activities affect foreign production possibilities. There are two kinds of possible spillovers: *spillovers into production* and *spillovers into research*. In the case of spillovers into production, foreign R&D capital is a direct input into another country's production function. In the case of spillovers into research, foreign R&D indirectly affects another country's production by influencing its accumulation of R&D, which is an input in that country's production function.

The methodology adopted in this paper is similar to that found in industrial studies of research spillovers.[5] The main difference is that the unit of analysis is a nation instead of a firm or industry. Overall, the results show that international knowledge spillovers into production and research activities do occur. Indeed, the most significant effect of public research is in generating international spillovers into research, because in terms of explaining private sector production, private research is more important than is public research.

3. Buiter and Kletzer [1991] also discuss this point.

4. See Lucas [1988], Romer [1990], and Grossman and Helpman [1991].

5. See Bernstein and Nadiri [1989], Griliches and Lichtenberg [1984], Levin and Reiss [1988], and Jaffe [1986].

Once private R&D is controlled for, public R&D is statistically insignificant in explaining private sector productivity growth.

The next section discusses the empirical specification. Section III describes the data and section IV presents the empirical results. Section V contains concluding remarks.

II. AN EMPIRICAL SPECIFICATION

The model used in this paper builds on Solow's [1957] approach but modifies it so that the total factor productivity term depends on research inputs. In most of the OECD countries, the public sector funds nearly 50 percent of national research. In Japan, the public sector funds less, about 20 percent.[6] In terms of performing research, however, the private sector does a much larger share. Although both performance and funding are important, this paper focuses on funding.

Publicly funded research and development may affect private sector production activities directly and indirectly. A direct effect may arise from the presence of public R&D capital as an input in the private sector production function. An indirect effect may arise from public research stimulating private research and thereby augmenting the stock of private R&D capital that is an input in the private sector production function. Likewise, international spillovers may arise through two kinds of channels. Through *spillovers into production*, research activity in one country may affect another country's production activities, and through *spillovers into research*, research activity in one country may affect another country's research activities. Thus this section consists of two parts: the first specifies the aggregate private sector production function; the second derives a private R&D investment equation.

Aggregate Private Sector Production Function

Consider the following aggregate production function:

$$Y = A\,F(K, H) \tag{1}$$

where K is the stock of private capital, H the stock of private labor measured in hours worked, Y private gross domestic product, and A an index of the technical efficiency of production. It is assumed that

$$A = A(R, R^*), \tag{2}$$

where R and R^* are the stocks of domestic and foreign R&D capital respectively. The stocks of research capital are proxies for the state of knowledge. The knowledge created by a private or public agent is added to the pool of existing knowledge, to which other agents potentially have access. Even if the benefits of research are fully appropriated by an agent, in the sense that an agent acquires a monopoly right to use the results of a research effort, the knowledge created may spread across sectors (or countries) through various communication channels such as publications, seminars, personal contacts, reverse engineering, joint ventures, and other means. Here knowledge is considered nonrival but partially excludable.[7] Finally, to the extent that some research knowledge may already be embodied in the private inputs K and H (private capital and labor), a significant A term could indicate the presence of excess social returns to R&D (not already captured in the private inputs).

Assume for now that R is the stock of *private* R&D. Public R&D will be introduced shortly. In an N-country world, the

6. Source: OECD Scientific, Technological, and Industrial Indicators Division (STIID) Data Bank.

7. The Romer [1990] model makes this distinction between knowledge spillovers and appropriability of the returns to R&D.

global stock of private research capital is given by

$$\sum_{j=1}^{N} R_j(t)$$

where the subscript j denotes the jth country. For country i, R_i represents its *domestic* stock of private research capital and R_i^* its *foreign* stock of private research capital; that is,

$$R_i^* = \sum_{j \neq i}^{N} \omega_j R_j(t),\ 0 \leq \omega_j \leq 1$$

where the weights, ω_j's, are technical distance terms used to reflect the fact that knowledge inputs from different countries are not perfect substitutes from the point of view of the domestic economy. These technical distance terms are constructed by defining a vector of characteristics (such as the functional composition of R&D) and identifying two countries as being technologically close neighbors if they have a similar vector of characteristics.[8] Specifically, the weights are constructed as follows:

Let vectors $f = (f_1, \ldots, f_k)$ and $f^* = (f_1^*, \ldots, f_k^*)$ be the functional composition of R&D in the domestic and foreign economy respectively, where $\Sigma f_i = 1$, $\Sigma f_i^* = 1$, $0 \leq f_i \leq 1$, and $0 \leq f_i^* \leq 1$. There are assumed to be k different types of research activities, such as electronics research, chemical research, and so on, so that f_i is the fraction of a country's private research budget allocated to activity i. The technological closeness between the two countries can be defined by θ, the "angle" between the two vectors f and f^*:

$$\cos\theta = (f \cdot f^*) / (\|f\|\ \|f^*\|)$$

where $\cdot$ denotes dot product and $\|\cdot\|$ the distance of a vector from the origin. Since f and f^* contain non-negative elements, cos θ varies from zero to one. Hence the weight assigned by the domestic country to country j's research is $\omega_j = (\cos\theta)_j$, where $\omega_j = 1$ if the two countries have identical functional compositions of R&D and $\omega_j = 0$ if their vectors f and f^* are orthogonal. The weight ω is nearer to unity the more similar are the two countries' research interests.[9] The underlying rationale is that each research sector in a country benefits most from research conducted in the same sector abroad and less from different sectors. The country as a whole therefore obtains the most benefits from a foreign country whose research composition parallels its own.

Substituting (2) into (1) gives, for country i,

$$(3) \qquad Y_{it} = Y(R_{it}, R_{it}^*, K_{it}, H_{it})$$

$$= C\exp[\alpha_0 f(t, cu_{it})] R_{it}^{\alpha_1} R_{it}^{*\alpha_2} K_{it}^{\alpha_3} H_{it}^{\alpha_4}$$

where C is a constant and exp is the exponential operator. The term $f(t, cu_{it})$ is some function of time and the capacity utilization rate, cu, and $\alpha_1, \ldots, \alpha_4$ are the output elasticities. The capacity utilization rate is used to control for cyclical influences and the time trend is used to model exogenous trend phenomena.

8. This approach is based on Jaffe [1986].

9. There are alternative ways to measure technological likeness. For instance Coe and Helpman [1993] use weights based on bilateral trade import shares in their construction of a spillover variable; that is, a country is assumed to receive relatively more knowledge spillovers from countries from which it imports relatively more goods and services. In this paper, the objective is to find out who are technological neighbors rather than find out what correlates with international knowledge spillovers. The assumption is that an economy can better make use of foreign R&D in its production and research activities if foreign R&D is similar to its own. Bilateral trade patterns do not necessarily provide information about the similarity of R&D between countries. For example, U.S.-Mexican trade is relatively large (compared to U.S. trade with other nations), but it is questionable whether the two are close technological neighbors.

Let a lowercase letter $x = \log X$, and omit for simplicity the country and time subscripts. Taking the logs of (3) gives

$$(4)\quad y = c + \alpha_0 f + \alpha_1 r + \alpha_2 r* + \alpha_3 k + \alpha_4 h.$$

With constant returns to scale in all the inputs, (4) becomes

$$(4')\quad yh = c + \alpha_0 f + \alpha_1 rh + \alpha_2 rh* + \alpha_3 kh$$

where $xh = \log(X/H)$ for $X = \{Y, R, R*, K\}$ and $x = \{y, r, r*, k\}$.

The first-difference of (4′) gives the growth accounting equation, which is estimated in the empirical section:

$$(5)\quad \Delta yh = \alpha_0 \Delta f + \alpha_1 \Delta rh + \alpha_2 \Delta rh* + \alpha_3 \Delta kh.$$

The stocks of research capital are each obtained by the cumulative sum of past gross investments adjusted for depreciation. However, there should be a time lag of m, where m is the number of years it takes for a flow of R&D spending to become useful in private production (or to go through the phase of generating marketable products or processes). This is equivalent to saying that the stocks of R&D in the production function, equation (3), are lagged m years. The value of m depends on whether research is predominantly basic, applied, or development oriented. The empirical section adopts $m \geq 3$ years.[10]

Private R&D Investment Equation

International spillovers into research are studied using the behavioral investment equation derived below. First, some additional notation is required:

R_p ~ stock of domestic private R&D capital

R_g ~ stock of domestic public R&D capital

R_p* ~ stock of foreign private R&D capital

R_g* ~ stock of foreign public R&D capital

Let I_p, I_g, I_p*, and I_g* be the gross investments in R_p, R_g, R_p*, and R_g* respectively. The R&D capital accumulation equations are then:

$$\Delta R_p = I_p - \delta R_p$$

$$\Delta R_g = I_g - \delta R_g$$

$$\Delta R_p* = I_p* - \delta R_p*$$

$$\Delta R_g* = I_g* - \delta R_g*$$

where δ is the rate of depreciation.

A representative firm maximizes its value:

$$(6)\quad V(t) = \mathrm{E}_t \sum_{s=t}^{\infty} [1/(1+r)]^{s-t}$$

$$\{Y[R_p(s), \ldots] - J[I_p(s), R_p(s)] - q(s) I_p(s)\}$$

by choosing a stream of R&D investments $\{I_p(s)\}$ for time $s = t, \ldots, \infty$, subject to

$$R_p(s) = I_p(s) + (1 - \delta) R_p(s-1)$$

and

$$J[I_p(s), R_p(s)] = (\psi/2)\,[I_p(s)^2/R_p(s)], \quad \psi > 0$$

where J is a convex installation cost function: adding a unit to the stock of R&D capital requires more than a unit of out-

10. A study by the U.S. Bureau of Labor Statistics [1989] discusses the issue of research-productivity lags, and finds that a lag of $m = 3$ might be apposite. The mean lag for basic research appears to be five years and applied research two years. A weighted average would then be three or four years.

put.[11] Y is the private output function, r the real interest rate, and q the price of R&D investment. The price of output is normalized to unity.

The Euler equation (solution) is

$$(7)\quad E_t\{Y_R(t) - \psi[I_p(t)/R_p(t)] + (\psi/2)[I_p(t)/R_p(t)]^2 - q(t) + [1-\delta)/(1+r)][\psi(I_p(t+1)/R_p(t+1)) + q(t+1)]\}=0$$

where Y_R is the marginal product of R_p.[12] E_t is a conditional expectations operator (given information known to the agent at time t). The firm cannot improve its value, at the margin, by transferring a unit of investment resources at time t to increase investment at time t+1 by $(1+r)/(1-\delta)$. A unit of resource saved at time t earns $(1+r)$ in the next period plus a gain in terms of the depreciation forgone—hence the division by $(1-\delta)$.

Removing the expectations operator (and replacing it with the ex-post error) and rearranging gives

$$(8)\quad I_p/R_p = (\gamma/\psi)q(-1) - (1/\psi)q + \gamma[(I_p(-1)/R_p(-1)) - 0.5(I_p(-1)/R_p(-1))^2] - (\alpha_1\gamma/\psi)Y_R(-1) + \varepsilon$$

where (–1) denotes the one-period lag, ε the error term (with conditional mean zero), α_1 the output elasticity of private R&D capital, and $\gamma = (1+r)/(1-\delta) > 1$. The lagged marginal productivity of private R&D capital should have a negative effect on current R&D investment because at the margin a higher lagged Y_R would have raised last period's R&D investment.

Let the investment price q in general equilibrium be a function of public and foreign research variables:

$$q = q(I_g/R_g, I_g^*/R_g^*, I_p^*/R_p^*, \ldots)$$

where the (I/R)'s are the ratios of gross investment to stock. The effect of public R&D investment on q is expected to be ambiguous. On the one hand, the public research sector competes with the private research sector for scarce resources so that an increase in public research may raise the marginal cost of research activity (by raising the prices of factor inputs such as scientists and engineers and laboratory capital) and thereby crowd out private R&D investment. On the other hand, public research activities may generate knowledge spillovers to the private research sector (through technology transfer and other information dissemination channels) so that an increase in public research enhances the productivity of privately employed research inputs and thereby lowers the marginal cost of private R&D activity. Thus there are opposing influences of public research on q.

Similarly, foreign public and private research spillovers should help lower domestic q, but it is also possible among large open economies for foreign research investments to generate financial and resource crowding-out pressures on domestic research investments.

Suppose that q is a linear function of domestic public R&D accumulation (ignoring the foreign R&D variables for the moment):

$$q = \text{constant} + \lambda(I_g/R_g).$$

Then (8) can be written as

11. The importance of adjustment costs associated with R&D investment is well documented in previous work; for example, in Bernstein and Nadiri [1989] and Hall [1992]. High adjustment costs help explain the stability of R&D investment relative to fixed investment over time.

12. A similar derivation is contained in Hall [1992] who analyzes R&D tax policy.

$$(9) \qquad I_p/R_p = \text{constant} + \beta\, IR_g + \gamma\, IN(-1) - \varphi\, Y_R(-1) + \varepsilon$$

where

$$IR_g = (I_g/R_g) - \gamma[I_g(-1)/R_g(-1)],$$

$$IN(-1) = [I_p(-1)/R_p(-1)] - 0.5[I_p(-1)/R_p(-1)]^2,$$

and

$$\beta = -\lambda/\psi,\ \varphi = \gamma\alpha_1/\psi.$$

Equation (9) is estimated below; the capacity utilization rate and foreign R&D variables are also added as explanatory variables. If $\beta > 0$ (< 0), public research investment stimulates (crowds out) private research investment on balance. Note that (9) is limited in that λ and ψ cannot be identified separately without further restrictions. Moreover, different functional forms could be specified for the investment price (q) function, installation function, and the production function which would alter the form of (9). Nonetheless, (9) illustrates the kind of behavioral equation which emerges from an intertemporal optimization framework.

Before proceeding, it is worth summarizing some key assumptions made: Hicks-neutral technical progress; Cobb-Douglas production function; constant returns to scale; common factor restrictions in equation (5); common depreciation rates for all stocks; and ability to control for business cycles. First, in preliminary specification tests, the following restrictions could not be rejected: constant returns; common factor restrictions (of unity on the lagged variables); and the Cobb-Douglas specification (versus a translog). Secondly, whether knowledge capital enters in Hicks or Harrod-neutral fashion, the formulation in equation (3) is the same when the production function is Cobb-Douglas. Thirdly, the foreign and domestic rates of depreciation are assumed to be the same given the assumption of identical technologies across countries. However, if the depreciation rate for private R&D exceeds that for public, one result in this paper (that private research is more important than public for private production) could be altered. But since the depreciation rate for knowledge is inversely related to the difficulty of appropriating it, if anything, the depreciation rate for public knowledge should be higher. Furthermore what determines the efficacy of public versus private research is the composition of research; public research consists of investments in knowledge which do not contribute directly to final private production, for example defense research. Finally, business cycles are controlled for using the capacity utilization rate. The alternative of time-averaging the data (every three years) to smooth out cyclical fluctuations produced very similar results.[13]

III. DATA DESCRIPTION

The panel data set covers ten OECD countries: Belgium, Canada, France, Germany, Italy, Japan, the Netherlands, Sweden, the U.K., and the U.S. Together these countries fund roughly 95 percent of the world's research activities. Data have been collected for the period 1970–87. U.S. data are from the Department of Commerce, Bureau of Economic Analysis. The corresponding data for the other countries are from the OECD's *National Accounts* (Vol. 2) and *Labour Force Statistics*. Work hours are from the International Labour Office's *Yearbook of Labour Statistics*. Research data are obtained from the OECD's *Science and Technology Indicators* databank, and capacity utilization rates from the OECD's *Main Economic Indicators*.

13. The results of these preliminary tests are available in an appendix from the author upon request.

Data on output and investment are converted into real 1985 U.S. dollars using the purchasing power parity rates given in the OECD's *National Accounts* (Vol. 1). Total hours worked are constructed by multiplying average hours worked per year by total civilian employment (in the same year). Labor supply is defined in terms of hours worked in order to take into account the intensity of work per average worker, which varies across countries and over time. As in Mankiw et al. [1992] and Lichtenberg [1992], I assume an exogenous growth of efficiency of labor of 2 percent per year.[14] This helps avoid over-attributing increases in productivity growth to investments in research. Finally, since the capacity utilization rates of different countries are not all measured on the same scale, the rates have been converted into an index series in which 1985 = 100.

The stocks of physical and R&D capital are constructed for each country using the perpetual inventory method, discussed in the appendix. Following Mankiw et al. [1992] and Lichtenberg [1992], a depreciation rate of 3 percent is assumed for all stocks.[15] Because of the assumption that research flows add to the stock of knowledge capital with a three-year lag, the "effective" sample period is 1973–87, while that of R&D investments is 1970–84.

Table I shows what share of the "global" pool of research capital is accounted for by each of the ten countries. Here the global stocks of private and public research capital are obtained by a simple sum of the national stocks (all in real 1985 U.S. dollars). Each country's share of the global stock is determined by dividing its stock by the global stock. As the table shows, the U.S. accounts for the bulk of world research capital created, namely for half of the global stock of private R&D and for more than half of the global stock of public R&D.

The functional composition of public and private research is used to construct the weights for identifying technological neighbors.[16] The weights are then used to derive a spillover stock value for each country for each year. The weights are country specific and time varying since they are based on information on the functional composition of R&D between each pair of countries at each point in time. Table II shows some sample weights. For example, Belgium's public R&D has a mean weight of 0.28 in the U.S.'s foreign public R&D stock, while the U.K.'s public R&D has a mean weight of 0.94 in the U.S.'s foreign public R&D stock. These indicate that on average, over the sample period, 28 cents of every $1 of Belgian public research spilled into the U.S., while 94 cents of every $1 of U.K. public research spilled in. Note that a country receives more foreign research spillovers if either: (1) foreigners conduct more research, or (2) the country and the rest of the world become closer technological neighbors so that more of foreign research output can be used in domestic research and production activities.

IV. EMPIRICAL RESULTS

This section consists of three parts: the first compares the effects of public and private R&D on productivity growth; the second examines international spillovers into production; and the third examines international spillovers into research.

14. This is done by multiplying the stock of labor hours, H, by $\exp(0.02T)$, where exp is the exponential operator and T time.

15. Experimenting with a depreciation rate of 10 percent produced similar qualitative and quantitative results.

16. The functional categories of public research are: agriculture, industry, energy, infrastructure, environment, health and social services, space, and defense. The functional categories of private research are: electronics and electrical, chemicals, aerospace, other transportation, basic metals, machinery, chemical-linked, and services.

TABLE I
Percentage Shares in Global R&D Stocks by Country
(Average 1973–87)

	USA	UK	SWE	NETH	JPN	ITA	GER	FRA	CAN	BEL	Total
Public:	55.8	7.5	1.7	2.6	7.4	3.5	7.7	7.4	3.9	2.5	100
Private:	50.1	6.9	0.9	2.4	14.9	5.4	9.9	7.1	1.9	0.5	100

Source: OECD Scientific, Technological and Industrial Indicators Division (STIID) Data Bank.

TABLE II
Technical Distance Weights: Sample Means

Public Sector Research

	USA	UK	SWE	NETH	JPN	ITA	GER	FRA	CAN	BEL
USA	1.00	0.94	0.90	0.43	0.33	0.40	0.71	0.93	0.40	0.28
UK		1.00	0.86	0.40	0.30	0.39	0.69	0.96	0.42	0.25
SWEDEN			1.00	0.68	0.49	0.60	0.87	0.92	0.63	0.58
NETHERLANDS				1.00	0.83	0.70	0.75	0.57	0.93	0.84
JAPAN					1.00	0.82	0.72	0.48	0.85	0.78
ITALY						1.00	0.89	0.58	0.66	0.87
GERMANY							1.00	0.83	0.70	0.81
FRANCE								1.00	0.56	0.47
CANADA									1.00	0.78
BELGIUM										1.00

Private Sector Research

	USA	UK	SWE	NETH	JPN	ITA	GER	FRA	CAN	BEL
USA	1.00	0.95	0.76	0.57	0.77	0.77	0.88	0.95	0.82	0.66
UK		1.00	0.74	0.51	0.83	0.80	0.91	0.98	0.90	0.80
SWEDEN			1.00	0.54	0.94	0.89	0.87	0.78	0.76	0.70
NETHERLANDS				1.00	0.54	0.53	0.61	0.48	0.49	0.58
JAPAN					1.00	0.92	0.95	0.86	0.86	0.87
ITALY						1.00	0.89	0.86	0.81	0.81
GERMANY							1.00	0.93	0.86	0.88
FRANCE								1.00	0.90	0.80
CANADA									1.00	0.86
BELGIUM										1.00

Note: Each entry represents technological similarity between R&D of row country and R&D of column country.

TABLE III
Private versus Public R&D

Dependent Variable: Δyh (Number of Observations = 150)

	constant	$\Delta r_p h$	$\Delta r_g h$	Δkh	*cu*	*time*	Adj R^2	Hausman χ (*p*-value)
A.								
OLS	−0.87	0.11	—	0.368	0.2	−0.0032	0.38	
	(0.14)	(0.035)		(0.052)	(0.03)	(0.0004)		
FE	—	0.11	—	0.377	0.21	−0.0033	0.33	
		(0.045)		(0.056)	(0.032)	(0.00045)		
RE	−0.88	0.11	—	0.37	0.198	−0.0032	0.33	$\chi^2(4) = 0.64$
	(0.14)	(0.037)		(0.053)	(0.03)	(0.00044)		(0.96)
B.								
OLS	−0.79	—	0.076	0.363	0.18	−0.003	0.35	
	(0.14)		(0.038)	(0.054)	(0.03)	(0.00047)		
FE	—	—	0.089	0.372	0.2	−0.003	0.32	
			(0.045)	(0.057)	(0.032)	(0.00047)		
RE	−0.82	—	0.08	0.37	0.18	−0.003	0.31	$\chi^2(4) = 1.19$
	(0.14)		(0.039)	(0.054)	(0.03)	(0.00046)		(0.88)
C.								
OLS	−0.92	0.23	−0.14	0.387	0.21	−0.0037	0.38	
	(0.14)	(0.08)	(0.083)	(0.053)	(0.033)	(0.00051)		
FE	—	0.184	−0.08	0.383	0.21	−0.0035	0.32	
		(0.116)	(0.12)	(0.057)	(0.034)	(0.00056)		
RE	−0.92	0.23	−0.14	0.387	0.21	−0.0037	0.34	$\chi^2(5) = 1.35$
	(0.14)	(0.08)	(0.084)	(0.053)	(0.031)	(0.00051)		(0.93)

Notes: *yh*, *kh*, $r_p h$, $r_g h$, and *cu*, are the logs of output per work hour, physical capital per work hour, private R&D capital per work hour, public R&D capital per work hour, and the capacity utilization rate respectively. Hausman χ is the Hausman test statistic comparing fixed effects (FE) and random effects (RE). Standard errors are in parentheses.

Private versus Public Research

Table III presents OLS, fixed effects (FE), and random effects (RE) estimates of the growth accounting equation (5) with domestic public and private research inputs. Here, $r_p h = \log(R_p/H)$ and $r_g h = \log(R_g/H)$. Cases A and B of Table IV examine private and public R&D separately and case C examines them jointly. No specific individual-effects variables are modelled. The individual effects are assumed to be reflected in the error term. Examples of unobserved heterogeneities might include institutional or cultural factors which affect a country's level of technical efficiency. The Hausman test statistics of the fixed effects versus random effects models

TABLE IV
Spillovers into Production

Dependent Variable: Δyh

	constant	$\Delta r_p h$	$\Delta r_p h*$	Δkh	*cu*	*time*	Adj R^2	Hausman χ (p-value)
Case 1: Total Pool (Number of Observations = 150 N = 10 countries and T = 15 years)								
OLS	−0.95	0.08	0.18	0.33	0.21	−0.003	0.42	
	(0.13)	(0.035)	(0.053)	(0.052)	(0.03)	(0.00043)		
FE	—	0.042	0.18	0.33	0.22	−0.003	0.35	
		(0.052)	(0.07)	(0.058)	(0.032)	(0.00046)		
RE	−0.96	0.069	0.17	0.33	0.21	−0.003	0.37	$\chi^2(5) = 1.62$
	(0.13)	(0.039)	(0.056)	(0.052)	(0.03)	(0.00042)		(0.9)
Case 2: Excluding USA (Number of Observations = 135 N = 9 countries and T = 15 years)								
OLS	−1.03	0.065	0.17	0.323	0.23	−0.0034	0.45	
	(0.14)	(0.039)	(0.059)	(0.053)	(0.031)	(0.00044)		
FE	—	0.029	0.18	0.335	0.24	−0.0034	0.39	
		(0.059)	(0.077)	(0.06)	(0.034)	(0.00046)		
RE	−1.04	0.059	0.17	0.327	0.23	−0.0034	0.4	$\chi^2(5) = 1.22$
	(0.14)	(0.041)	(0.061)	(0.053)	(0.03)	(0.00043)		(0.94)
Case 3: USA, Ger, Japan (Number of Observations = 45 N = 3 countries and T = 15 years)								
OLS	−0.4	0.18	−0.064	0.25	0.092	−0.0026	0.31	
	(0.26)	(0.058)	(0.07)	(0.086)	(0.057)	(0.00068)		
FE	—	0.095	0.017	0.24	0.11	−0.0024	0.17	
		(0.085)	(0.08)	(0.088)	(0.055)	(0.00067)		
RE	−0.45	0.14	−0.025	0.25	0.102	−0.0025	0.2	$\chi^2(5) = 3.05$
	(0.25)	(0.061)	(0.072)	(0.086)	(0.055)	(0.00066)		(0.69)

Notes: $r_p h*$ = log of foreign private R&D capital per work hour. See also notes to Table III. The Hausman tests again show that the null of no misspecification cannot be rejected.

do not indicate rejections of the null of no correlation between the explanatory variables and unobserved heterogeneities.

The results indicate that private R&D has an output elasticity of 0.11, compared to an output elasticity of 0.37 for physical capital. Public R&D has an output elasticity that is smaller, about 0.08. When the two stocks are examined jointly, it is seen that private R&D is the more important determinant of productivity growth (at the aggregate national level). In fact, once private R&D is controlled for, the public variable is no longer significant at the 5 percent significance level. This is not to suggest that public research cannot influence productivity growth, for it may do so indirectly by stimulating private research investment. This possibility is examined below in this section. In case B of Table III, public R&D proxies for the effects of the omitted variable, private R&D. Once pri-

vate research is explicitly controlled for, the direct effect of public research is weakly negative, as might be the case if public research spending has crowding-out effects which adversely affect private output growth.

Note that the parameter estimates of capital, the capacity utilization rate, and time are stable across the three cases. The positive coefficient of the capacity utilization variable (*cu*) indicates that productivity changes have been procyclical, and the negative coefficient on time indicates that during the sample period productivity followed a declining trend. The growth accounting specification explains about 31–38 percent of the changes in productivity over the sample period, leaving room for other explanatory variables such as human capital or trade.

Spillovers into Production

In Table IV, only the private research variables are added to the production function, since public research variables are insignificant when added together with those of private research. Here, $r_p h* = \log(R_p*/H)$. Case 1 contains the pooled results of all ten countries. Case 2 takes the U.S. out of the sample and excludes the stock of U.S. private R&D from the stock of foreign private R&D. The reason for examining this case is that since the U.S. accounts for the bulk of world research activities, it is of interest to see whether there exist international spillovers among the remaining nine countries. Case 3 pools only the top three major R&D countries: the U.S., Japan, and Germany. This case provides evidence on whether these three countries receive any foreign knowledge spillovers from the remaining seven countries. This subsection ends by examining the sensitivity of the results to the length of the lag between research and productivity growth and to measurement error.

The spillover effect is captured in the $\Delta r_p h*$ variable, which in case 1 is significant (at better than the 1 percent significance level). The spillover variable has an estimated output elasticity of 0.17–0.18. The presence of this variable reduces the estimated output elasticity and statistical significance of domestic private research. Thus, as a determinant of private sector productivity, foreign private research is statistically the more significant factor. Since the bulk of global private research capital is created by a few major R&D countries, foreign private knowledge spillovers on the whole tend to dominate the effects of domestic private knowledge.

However, domestic private research has a higher rate of return than does foreign. The sample mean ratio of foreign private R&D stock to output is 3.63, so that the estimated rate of return to foreign private research is 0.047 (= 0.17/3.63), while the sample mean ratio of domestic private R&D stock to output is 0.16, so that the estimated rate of return to domestic research is 0.44 (= 0.07/0.16)—using random effects estimates.[17] In other words, a $1 increase in the stock of domestic private R&D raises domestic private output per work hour by 44 cents, while a $1 increase in the stock of private R&D abroad raises it by 4.7 cents. Thus, while a 1 percent change in the stock of foreign private research capital has a larger effect on domestic productivity growth than does a 1 percent change in the stock of domestic private research capital, one must consider that the stock of foreign private R&D is much larger than the stock of domestic private R&D (except for the U.S.).

The rate of return estimates suggest three points. First, if each of the other nine countries abroad increases its own private research stock by $1, domestic private output per work hour increases by 42.3 cents

17. The rate of return to R&D is calculated as the output elasticity of R&D times the ratio of private output to the stock of R&D.

(or 9 times 4.7). Thus if, through international coordination, every country invests an additional $1 in private research, both domestic and foreign private R&D yield nearly the same total return. Secondly, the fact that domestic private R&D has the higher rate of return may explain (partially) why countries engage in research rather than free-ride on the research activities of the rest of the world, since substituting $1 of foreign private research for $1 of domestic, holding everything else constant, leads to a net loss in domestic output.[18] Thirdly, $1 of domestic private research has an average external rate of return (i.e. rate of return to the rest of the world) of 4.7 cents or a total external rate of return of 42.3 cents. The failure of domestic researchers to take into account these external benefits results in an inefficient level of international research activity.

For comparison, the rate of return to private fixed capital investment is 17 cents. This estimate is based on an output elasticity of private fixed capital of 0.33 and the sample mean ratio of the stock of private fixed capital to output of 1.9. The higher rate of return to private research investment, compared to that of private fixed investment, is found in other studies.[19]

When the U.S. is not included in the sample (case 2), there is still evidence of international spillovers into production (among the other nine countries). The spillover effects are quantitatively similar. Again, while foreign private R&D has a higher output elasticity than does domestic private R&D, the latter has a higher rate of return, of 39 cents, than the former, which has a rate of return of 8 cents. These rates are based on random effects estimates and on the sample mean ratio of domestic private R&D stock to output of 0.155 and the sample mean ratio of foreign private R&D stock to output of 2.1.

The results of case 3 are opposite to those of cases 1 and 2. For the top three R&D countries that, according to Table I, account for 70 to 75 percent of the stock of global private R&D capital, domestic private research is much more important than foreign, spilling over from the other seven countries, in explaining domestic productivity growth. (Here the stock of foreign private R&D includes just the private research stocks of the seven other countries). The relative importance of foreign research vis-'a-vis domestic research is therefore sensitive to the inclusion of certain countries. For this smaller group of countries, domestic private R&D has an output elasticity of 0.14 (from random effects estimation) and a rate of return of 70 cents (given the sample mean ratio of domestic private R&D stock to output of 0.19). Overall, the impression given in cases 1 through 3 is that the benefits of foreign spillovers are asymmetrical: research spillovers that have significant productivity effects go from the large R&D nations to the smaller, but not vice versa.

Table V shows the results of varying the length of the lag between research and productivity growth. It has been assumed that gross R&D investment flows take three years to affect productivity. This lag length has also been assumed to be the same for both domestic and foreign R&D. It may be that it takes longer for foreign research to spill into a country. In Table V, the net investments in R&D are lagged up to six years, which is equivalent to lagging gross investments up to nine years. The sample period is maintained at 1979–87 in order to accommodate the longest lag (as research data begin in 1970) and to vary

18. Another reason for engaging in domestic research is that a country will not be able to benefit from knowledge spillovers unless it conducts some of its own research. This is implicit in the weights used to construct spillover research stocks. If a country does little or no research, the spillover weights will be low, and thus little or no foreign knowledge should spill into the country.

19. For example, Bartelsman [1990], Griliches and Lichtenberg [1984], and U.S. Department of Labor [1989].

TABLE V
Sensitivity to Lag Structure of R&D

Dependent Variable: Δyh (Number of Observations = 90 N = 10 countries and T = 9 years)

Lag Length:	*constant*	$\Delta r_p h(-i)$	$\Delta r_p h*(-j)$	Δkh	*cu*	*time*	Adj R^2
$i=0, j=0$	–0.86	0.117	0.174	0.373	0.189	–0.0027	0.31
	(0.2)	(0.044)	(0.073)	(0.072)	(0.044)	(0.00086)	
$i=1, j=1$	–0.99	0.118	0.228	0.366	0.217	–0.0033	0.35
	(0.2)	(0.04)	(0.069)	(0.068)	(0.044)	(0.00082)	
$i=2, j=2$	–1.02	0.143	0.307	0.31	0.224	–0.0034	0.44
	(0.17)	(0.039)	(0.073)	(0.065)	(0.038)	(0.0007)	
$i=3, j=3$	–0.97	0.139	0.405	0.344	0.213	–0.0046	0.50
	(0.17)	(0.036)	(0.069)	(0.059)	(0.036)	(0.00073)	
$i=4, j=4$	–0.71	0.093	0.316	0.41	0.157	–0.0041	0.36
	(0.18)	(0.044)	(0.078)	(0.067)	(0.039)	(0.00082)	
$i=5, j=5$	–0.66	0.088	0.146	0.42	0.145	–0.0034	0.29
	(0.19)	(0.046)	(0.079)	(0.073)	(0.042)	(0.00086)	
$i=6, j=6$	–0.61	0.079	0.113	0.43	0.135	–0.0031	0.26
	(0.2)	(0.054)	(0.088)	(0.077)	(0.044)	(0.00092)	
$i=0, j=1$	–0.97	0.115	0.22	0.369	0.212	–0.0031	0.33
	(0.2)	(0.047)	(0.074)	(0.069)	(0.044)	(0.00078)	
$i=0, j=2$	–1.03	0.12	0.34	0.31	0.225	–0.0031	0.42
	(0.19)	(0.04)	(0.07)	(0.066)	(0.041)	(0.00077)	
$i=0, j=3$	–1.01	0.1	0.43	0.35	0.222	–0.004	0.47
	(0.18)	(0.043)	(0.074)	(0.063)	(0.039)	(0.00074)	
$i=0, j=4$	–0.81	0.12	0.31	0.37	0.179	–0.0034	0.38
	(0.18)	(0.042)	(0.076)	(0.066)	(0.04)	(0.0008)	
$i=0, j=5$	–0.72	0.113	0.18	0.38	0.158	–0.003	0.31
	(0.2)	(0.046)	(0.075)	(0.072)	(0.043)	(0.00084)	
$i=0, j=6$	–0.69	0.116	0.14	0.39	0.151	–0.0026	0.29
	(0.2)	(0.047)	(0.081)	(0.074)	(0.044)	(0.00089)	

Notes: Lag length: constant. The sample period is 1979–87. For reasons of space, only the random effects estimates are reported. In none of the panel regressions could the null of no misspecification be rejected.

the lag lengths while holding everything else constant. The first regression assumes no additional lags (other than the three-year lags already built into the research stock variables). The results are of course slightly different from those in case 1 of Table IV because the latter's sample period is 1973–87; in particular the output elasticity of domestic private R&D is higher in 1979–87.[20] This first regression is shown as a benchmark for the rest. The next six regressions progressively increase

20. Nonetheless an F-test shows that overall coefficient stability across the subsamples 1973–78 and 1979–87 cannot be rejected, using the first regression equation with $i=j=0$. The appropriate F-statistic (based on random effects results) is 1.57, which is below the critical value $F_{0.05}$ (6,138) = 2.1.

the lag length. The evidence seems to point to an inverted-V relationship between productivity growth and the length of the lag—that is, the output elasticities of both domestic and foreign private R&D initially increase as the lag is lengthened and then decrease after some point. For example, the productivity effect of net foreign private research investment diminishes after it is lagged more than three years. Indeed, when it is lagged six years, it is statistically weak, with a significance level of 20 percent. The productivity effect of net domestic private research investment diminishes after it is lagged more than two years. It too is statistically weak when lagged six years—with a significance level of 15 percent. The results suggest not only that it takes time for research to contribute to productivity growth but also that as time goes by, the productive benefits of R&D investment can dissipate. Note also that the adjusted R^2 initially increases and then decreases as the lag length is increased.

The last six regressions assume that it takes longer for foreign research than for domestic research to affect domestic productivity growth. Again, the peak effect of foreign private research on domestic productivity growth occurs when net foreign private research investment is lagged three years. The estimated output elasticity of domestic private R&D remains in the range of 0.1–0.12. In summary, the measured productivity effects of research are sensitive to the specification of lag length. In particular, the base assumption of three years underestimates the productivity effects of both domestic and foreign private research.

Finally, a discussion of measurement errors. If the "weights" (based on functional compositions of R&D) inaccurately measure technological closeness, the spillovers will be measured with error. A Hausman specification test can be used to test for the presence of measurement errors which make the error term in Table IV correlated with the spillover variable.[21] Let $\Delta r_p h* = \Delta r_p h*^T + v$ where v is the measurement error and $\Delta rph*^T$ the true net investment in foreign private R&D. As for where v comes from, it is assumed that in each year all the weights are off by the same factor. To see this, let the *true* stock of private research spillovers (for the home country) from the other N-1 countries be

$$R_p^{*T} = \omega_1 R_p^1 + \ldots + \omega_{N-1} R_p^{N-1}$$

and the actual stock used in the empirical analysis be

$$R_p^* = v_1 \omega_1 R_p^1 + \ldots + v_{N-1} \omega_{N-1} R_p^{N-1}$$

$$= v'(\omega_1 R_p^1 + \ldots + \omega_{N-1} R_p^{N-1}) = v' R_p^{*T}$$

where $v' = v_1 = \ldots = v_{N-1}$ is the common measurement error in the weights. Of course these errors v_i need not be the same for every weight ω_i. The concern is whether errors in measuring ω cause the spillover stock R_p* to be overestimated or underestimated. It is possible to overestimate one country's ω and underestimate another's, and yet for $R_p* = R_p^{*T}$. Thus v' can be interpreted as the overall factor by which the true stock of research spillovers is overestimated or underestimated. Dividing by labor hours H, taking logs, and first-differencing in order to obtain net investment, gives $\Delta r_p h* = \Delta r_p h^{*T} + v$, where $v = \log(v'/v'(-1))$.

The stock of R&D scientists and engineers in the private sector is used as an instrument since it is quite correlated with the stock of private R&D, and should not be correlated with the error term in Table IV if it is also lagged three years. The simple correlation between the stock of private R&D scientists and engineers per

21. See Hausman [1978], pp. 1259–60.

1000 work hours and the stock of private R&D per work hour is 0.78.

Let seh^* denote the log of the stock of foreign private R&D scientists and engineers per 1000 hours worked. After regressing net foreign private investment in research ($\Delta r_p h*$) on foreign investment in research scientists and engineers ($\Delta seh*$), the residuals (call it w^*) are included as a right-hand-side variable in the original equation (estimated in Table IV). The coefficient of w^* just equals the difference between the OLS estimate and the instrumental-variables (IV) estimate of the coefficient of $\Delta r_{ph}*$. Thus under the null hypothesis of no measurement error, the coefficient of w^* equals zero since OLS and instrumental variables estimation yield the same consistent estimate (although the instrumental variables estimate is inefficient). Under the alternative hypothesis, OLS is inconsistent and instrumental variables consistent; both will yield different estimates and the coefficient of w^* will be non-zero. A t-test on the coefficient of w^* can therefore be used to test for the presence of measurement error.

The results are as follows (using the full sample of 150 observations):

$$w* = \Delta r_p h* - \underset{(0.0022)}{(0.0082} + \underset{(0.063)}{0.61}\ \Delta seh*),$$

$$R^2 = 0.39$$

$$\text{Fitted } \Delta yh = \underset{(0.14)}{-0.95} + \underset{(0.037)}{0.079}\ \Delta r_p h$$

$$+ \underset{(0.117)}{0.188}\ \Delta r_p h* + \underset{(0.052)}{0.33}\ \Delta kh$$

$$\underset{(0.149)}{-0.017}\ w* + \underset{(0.032)}{0.21}\ cu - \underset{(0.00053)}{0.0031}\ time,$$

$$\text{Adj } R^2 = 0.4$$

where estimation is by OLS and standard errors are in parentheses. Based on the t-statistic of −1.14 (= −0.017/0.149), the null of no measurement error is not rejected. The main effect of correcting for possible measurement error is to reduce the statistical significance of spillover research. This is consistent with what was found in Table IV when the full sample was split into groups, namely that the importance of spillover research varies by region.

Spillovers into Research

Table VI presents estimates of equation (9). In column (1), the growth in global public R&D capital is given by the ratio $(I_g + I_g*) / (R_g + R_g*)$. In column (2), the global public research variable is separated into domestic accumulation (I_g/R_g) and foreign accumulation (I_g*/R_g*); column (3) adds to column (2) the accumulation of foreign private R&D capital (I_p*/R_p*). Column (4) is column (3) repeated without the U.S. in the sample. Column (5) is column (4) with the foreign private research variable (I_p*/R_p*) replaced by just the ratio of U.S. gross private R&D investment to U.S. private R&D stock. The foreign gross investments in research, I_p* and I_g*, are also weighted by the ω's, like their stock counterparts, R_p* and R_g*.

Equation (9) is estimated by instrumental variables because the right-hand-side variables are likely to be correlated with the error term given that the optimizing agent chooses I_p and its lag $I_p(-1)$ simultaneously (that is, the agent's investment choice depends on the agent's future investment plans). Also, a correction for heteroskedasticity is required because the larger countries tend to do a greater amount of investment in research. Finally, (9) may also contain moving average errors because of errors in predicting the investment price q using public and foreign research variables. The presence of both q and its lag $q(-1)$ in (9) would induce these errors. Thus (9) is estimated by the Generalized Method of Moments, robust

TABLE VI
Spillovers into Research

Dependent Variable: I_p / R_p	(1)	(2)	(3)	(4) No USA	(5) No USA
Constant	0.018 (0.048)	-0.004 (0.044)	-0.044 (0.038)	0.0076 (0.045)	-0.07 (0.05)
Global Public R&D	0.67 (0.23)	—	—	—	—
Domestic Public R&D	—	-0.29 (0.13)	-0.28 (0.12)	-0.42 (0.12)	-0.29 (0.12)
Foreign Public R&D	—	0.56 (0.194)	0.37 (0.167)	0.62 (0.2)	0.45 (0.18)
Foreign Private R&D	—	—	0.3 (0.187)	0.18 (0.24)	—
USA Private R&D	—	—	—	—	0.52 (0.19)
$IN(-1)$	1.02 (0.03)	1.02 (0.026)	1.04 (0.027)	1.03 (0.025)	1.06 (0.028)
$Y_R(-1)$	-0.12 E-4 (0.11 E-3)	-0.55 E-4 (0.11 E-3)	-0.6 E-4 (0.98 E-4)	-0.6 E-4 (0.1 E-3)	-0.45 E-4 (0.9 E-4)
cu	-0.003 (0.0105)	0.0015 (0.0096)	0.0099 (0.0083)	-0.0013 (0.0098)	0.016 (0.011)
Adj R^2	0.915	0.92	0.924	0.92	0.93

Notes: $IN(-1)$ is the lagged installation cost variable and $Y_R(-1)$ the lagged marginal product of domestic private R&D capital. Estimation is by Generalized Method of Moments (robust to heteroskedasticity and first-order serial correlation). The instrument set consists of the constant term, the right-hand-side variables lagged twice and three times, and the growth rate of output and of the R&D stocks lagged twice and three times.

to heteroskedasticity and first-order autocorrelation.

The results in column (1) indicate that global public research stimulates domestic private research. For example, a 1 percent increase in the stock of global public R&D capital is associated with a 0.67 percent increase in domestic private R&D capital, which in turn is associated with an increase in productivity growth of 0.067 percent (= 0.675 × 0.1, where 0.1 is the approximate output elasticity of private R&D found in Tables IV through V). The breakdown of global public research in column (2) into its domestic and foreign components shows that domestic private research investment tends to be crowded out by domestic public research investment but be stimulated by foreign public research investment. On balance, total (do-

mestic plus foreign) public research is a positive determinant of domestic private research investment, according to column (1).

Column (3) shows that controlling for foreign *private* research reduces the estimated impact of foreign public research from 0.56 to 0.37; that is, a 1 percent increase in the stock of foreign public R&D increases the stock of domestic private R&D by 0.37 percent. Foreign private research, however, is less important than foreign public research in determining domestic private R&D investment. There are two possible reasons why public research generates stronger spillovers into research than does private research. The first is that public research is more basic, and private research more applied and developmental, so that knowledge flows from public sources have the potential to create wider research spillovers. The second is that the results of public research are less appropriable and less safeguarded than those of private research, thereby allowing greater spillovers from public research than from private.[22]

Column (4) indicates that, without the U.S. in the sample, foreign private research is not significant in determining domestic private research. The inference is that the remaining countries generate weak cross-national spillovers into private research. Knowledge spillovers from private research activities come predominantly from the U.S. One reason might be that the other nine countries provide stronger protection against privately generated knowledge being revealed abroad, through tighter patent laws and other exclusionary rules. A very large open economy like the U.S. may have difficulties implementing and enforcing such rules.[23] Public research among these nine countries, however, continues to generate positive external effects. The estimated impact of foreign public research capital (which excludes U.S. public research) is again large at 0.62. This is consistent with the results in columns (1) and (2) which omitted foreign private research (including U.S. private research); in column (4), including foreign private research (net of U.S. private research) does not help explain domestic private R&D investment, so that the measured impact of foreign public research is quite similar across columns (1), (2), and (4). Only when foreign private research includes U.S. private research is it significant. In that case, controlling for it reduces the measured impact of foreign public research to 0.37.

Column (5) also excludes the U.S. from the sample and verifies that the U.S. is a major producer of spillover benefits. Replacing the foreign private research variable in column (4) by U.S. private research shows that the U.S.'s contribution to global private research capital alone is an important determinant of domestic private research activity among the other nine countries. (Note that each of the other countries weights U.S. research differently.) A 1 percent increase in the stock of U.S. private R&D is estimated (on average) to generate a 0.52 percent increase in the stock of domestic private R&D. Furthermore, the estimated impact of foreign public research falls from 0.62 to 0.45. However, to determine whether the rest of the world's research stimulates U.S. private research requires estimating (9) for individual countries, a task for which a longer time-series dimension is needed in the panel data set.

22. Trajtenberg et al. [1992] verify that basic research is correlated with "basic outcomes" (defined as research outcomes that are steppingstones to further technological developments) and that appropriability is lower for basic outcomes.

23. Another contributing factor is that U.S. firms have taken a leading role in dispersing their research facilities abroad and developing linkages with foreign research institutions and companies. U.S.-Europe and U.S.-Japan linkages are far more numerous than Europe-Europe or Europe-Japan linkages. See OECD [1992], part II, chapter 4.

As for the other variables in (9), the coefficient of the installation cost term, $IN(-1)$, which gives the value of γ, exceeds unity, as expected. The lagged marginal product term, $Y_R(-1)$, is largely insignificant.[24] Private research investment is weakly cyclical, according to its relation to the capacity utilization rate. This would be consistent with the observation that R&D investment data are relatively of low frequency.

V. CONCLUSION

The empirical findings support the view that there are international technological spillovers generated by national research investments. The main results are as follows: first, private sector research is a more important determinant of private sector productivity growth than is public sector research. Public research, however, does generate cross-national spillovers into research, so that public research can contribute to productivity growth indirectly by stimulating private R&D capital accumulation.[25] One hypothesis as to why private research affects productivity growth directly while public research affects it indirectly (by influencing private research) is that public R&D is largely basic, making it conducive to research spillovers, while private R&D is largely applied and developmental, making it more connected to private sector production activities.[26] Further research into this should help clarify the reasons.

The second main result is that there are technological spillovers into production with or without the U.S. in the sample of countries. The quantitative effects of spillovers from foreign research are similar whether the U.S. is included or not. In the case of spillovers into research, no significant spillovers from foreign private research into domestic private research can be captured unless the U.S. is included in the sample. In general, because a few countries (like the U.S.) conduct the bulk of world R&D, the spillover research variables tend to dominate their domestic counterparts in explaining productivity growth and private research investment. This illustrates that some countries receive more foreign knowledge spillovers than they generate and that others generate more than they receive.

In conclusion, an implication of this study is that technological externalities should receive greater attention in the literature on international economic policy coordination. Currently, no formal international mechanisms exist for coordinating science and technology policies. Thus one extension of this study is to explore how nations could, if at all, coordinate their fiscal and industrial policies to improve the global allocation of research resources and distribution of benefits. Another extension is to study foreign knowledge spillovers using disaggregated, sectoral-level data.

24. When the installation cost term, $IN(-1)$, is not modelled, the lagged marginal productivity term is usually significant at about the 10 percent significance level. An explanation is that firms gain, over time, relatively more from reductions in the marginal cost of installation as they accumulate research capital than from increases in the marginal product of R&D capital, which exhibits diminishing returns.

25. These findings are consistent with some U.S.-based studies: for example, Griliches and Lichtenberg [1984] and Bartelsman [1990] find using industry-level data that private R&D is more important than federal R&D to private production; Mansfield and Switzer [1984] and Leyden and Link [1991] find using micro data that federal R&D is a significant determinant of private R&D investment. Other studies, such as Levy and Terleckyj [1983] and Lichtenberg [1987], qualify the effects of public research on private.

26. Furthermore, research investments add to the productive stock of R&D capital with a lag, and the lag for basic research is typically longer than that for applied and developmental research.

APPENDIX
Derivation of Stocks

Stocks are derived from data on investment flows, using the perpetual inventory method:

$$\text{(A1)} \qquad R(t+1) = R(t)(1-\delta) + I(t+1)$$

where $R(t)$ is the stock of capital at the end of period t, $I(t+1)$ gross investment during $(t, t+1)$, and δ the geometric rate of depreciation. A value for the initial stock, $R(0)$, is obtained by backward recursive substitution:

$$R(t+1) = I(t+1) + (1-\delta)I(t)$$

$$+ (1-\delta)^2 I(t-1) + \ldots\ldots$$

or

$$R(t+1) = I(t+1)\{1 + (1-\delta)[I(t)/I(t+1)]$$

$$+ (1-\delta)^2[(I(t-1)/I(t+1)] + \ldots\} .$$

Let $1 + g(t+1) = I(t+1)/I(t)$. For simplicity let $g(t) = g$ for all t, where g is an historical average of the growth rate of investment:

$$\text{(A2)} \qquad R(t+1) = I(t+1)$$

$$\{1 + (1-\delta)/(1+g) + [(1-\delta)/(1+g)]^2 + \ldots\}$$

$$= I(t+1)(1+g)/(g+\delta) > 0$$

provided that both $(1+g)$ and $(g+\delta)$ are positive.

Thus given flow data from 1970 to 1987, a value for the stock of capital in 1970 can be found: $R(1970) = I(1970)\ (1+g)/(g+\delta)$. In the text, $\delta = 0.03$ and the value of g is obtained from the sample average since long-term historical flow data are not available. Both physical capital and R&D capital series are derived using (A1) and (A2).

In the case of R&D capital, however, investments in research are assumed to add to the stock of productive knowledge capital with a lag. Specifically, $R(t+1) = R(t)\ (1-\delta) + I(t+1-m)$, where m is the length of this lag. In the main text, $m \geq 3$ years.

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