Spring 1998

Looking for International Knowledge Spillovers: A Review of the Literature with Suggestions for New Approaches

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ANNALES D'ÉCONOMIE ET DE STATISTIQUE. – N° 49/50 — 1998

Looking for International Knowledge Spillovers A Review of the Literature with Suggestions for New Approaches

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ABSTRACT. – This paper reviews the recent empirical literature on international knowledge spillovers. I start by summarizing the theoretical models that have highlighted the potential importance of these spillovers. Then, drawing upon the older micro productivity research tradition, I lay out a simple conceptual framework (though not a formal theoretical framework) for thinking about the various kinds of knowledge transfers that may exist, how they might be mediated, and the means by which their effects might be traced empirically. I then review some influential empirical papers, demonstrating that empirical work to date may very well not have identified the effects the authors set out to measure. Finally, I describe some promising new approaches which may allow researchers in this field to identify more precisely, both conceptually and empirically, certain kinds of international knowledge spillovers.

Les externalités internationales de connaissance : survol de littérature et suggestions pour de nouvelles approches

RÉSUMÉ. – L'article fait le tour de la littérature empirique récente relative aux externalités internationales de connaissance. Je commence par résumer les articles théoriques qui ont bien fait apparaître l'importance que pouvait avoir de telles externalités. En me fondant ensuite sur la tradition plus ancienne des recherches microéconomiques en matière de productivité, je propose un cadre conceptuel simple (pas un modèle théorique) pour réfléchir sur les différents types possibles de transferts de connaissances, la façon dont ils pourraient être contrôlés, et les moyens de les repérer empiriquement. Je présente un certain nombre d'investigations empiriques présentées dans des articles importants, montrant qu'elles n'ont sans doute pas identifiées véritablement les effets qu'elles cherchaient à mesurer. Enfin je décris des approches nouvelles qui pourraient permettre aux chercheurs d'identifier plus précisément, conceptuellement et empiriquement, certaines des formes d'externalités internationales de connaissance.

* L. G. BRANSTETTER: U. C. Davis, NBER. The ideas expressed in this paper owe a substantial intellectual debt to discussions with Bee-Yan Aw, Magnus Blomstrom, Akira Goto, Ann Harrison, Adam Jaffe, Wolfgang Keller, Sam Kortom, Pierre Mohnen, Manuel Trajtenberg, Daniel Trefler, Ryuhei Wakasugi, Larry Westphal, and, especially, Zvi Griliches. I also thank two anonymous referees for their insightful comments. I note that parts of this paper draw heavily from my 1996 working paper, "Are Knowledge Spillovers Intranational or International in Scope?", and my 1996 Harvard Ph.D. thesis. All mistakes, errors, and misunderstandings are my own fault.

1 Introduction

Although the earliest models demonstrating the benefits of trade, due to David Ricardo, are based on technological differences between nations, both theoretical and empirical research in the Ricardian tradition has tended to take these differences as exogenous. Much of the work in international trade since the 1940s has been undertaken within the context of the Heckscher-Ohlin framework, in the most common version of which technology levels are assumed to be the same across countries. Even during the "Heckscher-Ohlin era", there were prominent voices within the international economics research community calling for studies of the role of technology and technological innovation in determining both the patterns of trade and the potential gains from trade, among them Raymond VERNON [1970]. Nevertheless, with a few exceptions, this extremely important nexus of questions has been all but ignored until very recently. Recent empirical tests of the Heckscher-Ohlin theory conducted by Daniel TREFLER [1993, 1995] have underscored the importance of this oversight, as he has convincingly demonstrated that the assumption of identical technology levels is one of the assumptions most strongly rejected by the data [1].

Two developments, which were more or less simultaneous, helped change this state of affairs. One was the introduction into theoretical international economics of methods of modeling imperfect competition and technological innovation. These methods were first developed in the fields of industrial organization and theory, then brought into international economics by such authors as KRUGMAN [1984, 1987], ETHIER [1982], ROMER [1990], GROSSMAN and HELPMAN [1991], and YOUNG [1991]. A reasonably complete exposition of some of the most influential of these modeling tools can be found in the book by GROSSMAN and HELPMAN [1991] although a rich literature has developed since its publication. These new models not only brought technological differences back into the core of the model, but they endogenized technological innovation, allowing the rate and direction of inventive activity to be affected by the global pattern of specialization and trade, and also allowing the pattern of trade to be, in turn, affected by the rate and direction of inventive activity, both in the global economy in aggregate and in individual countries. Bringing in technology in this fashion can affect both the nature and the degree of the gains from trade. The other development was the sudden and striking emergence of Japan, and later, other East Asian countries, as important suppliers of "high-technology" goods. This development, the political concerns it raised over "competitiveness", and the challenge it presented to the traditional view of comparative advantage as a static feature of the economy determined by

1. One of the other assumptions resoundingly rejected by the data is that of homotheticity of consumption across countries. The obvious "home bias" in consumption in most countries may be related to the discussion in this paper and elsewhere of "market access" informational spillovers.

exogenous factor endowments combined to give the new theories empirical relevance.

I lack space in this survey to do justice either to the range or to the depth of the theoretical models that have emerged thus far from this research tradition. However, I will note a few of its central conclusions, and sketch out the basic conceptual machinery that drives those conclusions. First, as was noted by ETHIER [1982], and in a dynamic context by ROMER and RIVERA-BATIZ [1991] and others, technological considerations can expand the gains from trade. Liberal trade policies provide domestic entrepreneurs with the possibility of exploiting a global market rather than merely a national one, inducing more R&D (or greater specialization) and leading to higher rates of growth and/or higher levels of welfare. By much the same logic, the negative impact of import restrictions can be magnified if they force domestic consumers or domestic producers to not only pay higher prices for the same range of consumer goods or producer intermediates, but also to have to make do with a narrower range of goods and intermediates (see ROMER [1990] and FEENSTRA [1992]). When consumer utility or producer productivity is a function of either the range of goods available or the level of quality of the available goods, the second-order effects of trade restrictions found in typical trade models can have first-order adverse welfare impact.

However, it has also been demonstrated that the gains from trade can be diminished or even overturned under some circumstances in these models [2]. Since these are also the circumstances under which technological developments can actually determine the long-run pattern of trade, they are worth closer examination.

2 Theoretical Foundations

The productivity research community has been interested in the causes, effects, and implications of R&D spillovers for a long time. A particularly detailed discussion of the issues appears in GRILICHES [1979]. "Partial equilibrium" theoretical treatments of the effects of R&D spillovers were presented by SPENCE [1984] and COHEN and LEVINTHAL [1989], among many others. However, this topic and its fundamental importance with regard to economic growth in the long run was introduced to a larger audience within economics through the "endogenous growth" and "growth and trade" literatures.

2. In these models, moving from autarky to free trade generates one-time welfare gains by enlarging consumption possibilities. However, if a country's comparative advantage is in a technologically stagnant sector, then it can be "trapped" by free trade into an equilibrium rate of output growth that is even lower than it would obtain under autarky. Thus, the static gains from trade can be offset by dynamic losses, see FEENSTRA [1994] and YOUNG [1991].

The theoretical contributions of GROSSMAN and HELPMAN [1990, 1991, 1995] have had a strong impact on empirical research on international R&D spillovers. Grossman and Helpman present a general equilibrium framework of two trading economies in which the rate of world economic growth is determined by the rate of innovation. R&D activity requires private investment of resources, but it also utilizes a stock of general knowledge – "the state of the art" – which is presumed to be costlessly accessible to all innovators. In turn, each innovation yields both a new product design (whose benefits the innovator can appropriate) and a unit addition to the stock of general knowledge. Over time, this foundation of knowledge grows, and this allows more innovation to occur without an increase in its resource cost. Thus, knowledge spillovers serve as "engines of endogenous growth", allowing economic growth to proceed indefinitely without diminishing returns setting in [3].

In this sort of framework, the impact of innovation on the global pattern of trade depends crucially on the assumptions one makes about the scope of knowledge spillovers. If knowledge spillovers are global in scope, then trade is still determined by the exogenous traditional forces of comparative advantage. On the other hand, if knowledge spillovers are intranational, then trade patterns can exhibit path dependence. Comparative advantage itself can become endogenous. GROSSMAN and HELPMAN [1995] describe this process with the following example: "Suppose it is country A that begins with more research experience. Then initially this country's researchers have a competitive advantage in the research lab, and they perform all of the world's R&D at time 0. But then additional knowledge accumulates in country A, while in the absence of international knowledge spillovers, the knowledge stock remains fixed in country B. So, country A's competitive lead in R&D widens and there is even greater reason for this country to conduct all the world's research in the next period. The initial lead is self-reinforcing and eventually country A comes to dominate production in the high-technology sector [4]." The presence of this mechanism means that an "accident of history" or a temporary policy that provides one country with a temporary advantage in the R&D-intensive sector "can have long-lasting implications for trade when there is a national component to the knowledge capital stock" [5].

Why might knowledge spillovers flow more easily within countries than across them? Several reasons immediately suggest themselves. First is geography – it is clearly easier for scientists and engineers to interact and

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3. This phrase was itself coined by GROSSMAN and HELPMAN.

4. This quote and the others in this paragraph are taken from "Technology and Trade" by GROSSMAN and HELPMAN, published as Chapter 2 in the *Handbook of International Economics*, vol. 3.

5. This is particularly well-phrased. If spillovers are *purely* intranational, the effects of a temporary policy can last forever. In the case of partial international spillovers, the Grossman-Helpman framework predicts that, in the very long-run, the world economy can eventually converge to the same steady-state equilibrium that obtains in the case of complete international spillovers. However, the process of convergence could take decades (or longer), so that temporary policies can indeed have "long-lasting", but not necessarily permanent effects in the case of partial international spillovers.

observe one another if they are geographically proximate. Compounding this is the issue of language, which also acts as a barrier to the transfer of knowledge across national boundaries. More important that either of these, however, may be the limited mobility of research personnel across national boundaries, as opposed to within them. Finally, the full set of regulatory barriers that makes transnational business more complicated and costly than business within a single country may also act to inhibit the cross-border flow of knowledge [6].

It is obvious that this parameter, namely the differential impact of intranational versus international knowledge spillovers, is an extremely important one, with strong implications not only for the predictions of the theoretical model but also the traditional trade economist's policy prescription of a liberal, laissez-faire trade policy. Thus it is not surprising that these theoretical results have inspired empirical work attempting to measure international knowledge spillovers. Unfortunately, the real world is not nearly so nice, neat, and symmetrical as the theoretical world constructed by Grossman and Helpman. In looking in the data for the empirical traces of international and intranational knowledge spillovers, it is important to keep in mind what phenomena the theory focus on and how we might be ablve to focus on that same phenomena in empirical work. Given this challenge, it seems worthwhile to review the taxonomy that GRILICHES [1992] has introduced to classify knowledge spillovers.

3 A Taxonomy of Spillover Effects

A knowledge spillover occurs when firm a is able to derive economic benefit from R&D activity undertaken by firm b without sharing in the cost firm b incurred in undertaking its R&D. Using this definition, we immediately make a distinction between spillovers *per se* and technology transfer, in which the innovator sells its right to use technology to another firm or establishes a subsidiary and transfers technology to it. As long as the innovator is able to appropriate all (or even most) of the surplus from the transfer, then there is no significant "externality".

Confining our attention for the moment to cases of actual spillovers, we can easily imagine at least two types. First, there is the case where a firm produces a new or improved product, but is unable to appropriate all of the surplus from its innovation because of its inability to perfectly price discriminate and due to existing competition with suppliers of substitute goods or, perhaps, the potential entry of imitators. In this case, the firm passes along some of the surplus to the purchasers of the goods. This is

6. I thank an anonymous referee for encouraging me to be more explicit about the reasons why knowledge spillovers are likely to have an intranational component.

an externality, to be sure, but it is what GRILICHES [1979, 1992] has termed a "precuniary externality". Purchasers are able to obtain a better input for less than their reservation price, and this can be a substantial gain. It is not, however, the kind of knowledge spillover that powers endogenous growth in the models of Grossman and Helpman. In this case, innovation occurs in the upstream sector, but the benefits spill over downstream. There is no presumption, though, that this financial windfall will create further innovation – *i.e.*, a shift in the production possibilities frontier – of the downstream sector. At most, it may allow firms in the downstream sector to move along their existing production possibilities frontiers to a more optimal point reflecting the effective change in input prices. This is the kind of adjustment we would expect in the wake of, say, an exogenous decline in oil prices. It is not the stuff of which endogenous growth is made. Without further innovation in the upstream sector, the benefits of which "leak" downstream thanks to competition, there will be no further growth.

As GRILICHES [1992] has pointed out, this kind of spillover can be contrasted with a disembodied "knowledge spillover". In this case, the new technological knowledge embodied in new goods produced by firm a is eventually "reverse-engineering" and becomes part of a general pool of knowledge – the "state of the art". Subsequent innovators are able to build upon this foundation of general knowledge, using it as a complement to their own R&D activities. With these kinds of spillovers, innovations tend to beget subsequent innovations, which, in turn, become part of the state of the art. It is ultimately this kind of spillover that can produce both endogenous growth and endogenous changes in the pattern of comparative advantage among nations [7].

To make this point more concretely, we note that in the late 1980s, there was a vigorous debate in the United States over what the federal government should do, if anything, to assist the American semiconductor industry in coping with what then seemed to be insurmountable competition from Japanese firms. In defending the Bush Administration's laissez-faire approach, economist Michael Boskin, then Chair of the Council of Economic Advisors, made the famous quip, "It doesn't matter whether America produces semiconductor chips or potato chips". In the absence of technological externalities, Professor Boskin is probably correct. Furthermore, if technological externalities are purely pecuniary in nature, Professor Boskin may still be right. As long as American consumers of semiconductor products have free access to Japanese semiconductor products, they will receive precisely the same level of pecuniary spillover as Japanese consumers when they purchase the product [8]. However, it

7. In modeling this sort of spillover, Grossman and Helpman abstract from the possibility of simple imitation by assuming perfect protection of intellectual property.

8. This will not necessarily hold in all conceivable circumstances. High transport or other trade costs could create *localized* pecuniary externalities. Alternatively, an appreciation of the yen relative to the dollar could make Japanese semiconductors more expensive for American consumers.

may be that, in fact, innovation in the semiconductor industry has the effect of abetting innovation in the computer industry, which further begets innovation in the software industry. These are knowledge spillovers. If they are strong and if they are purely or primarily *intranational* in scope, then Professor Boskin may be wrong. Boskin's successor, Professor Laura TYSON [1993], argued strongly that these types of knowledge spillovers do emanate from the semiconductor industry into other related sectors, and justified U.S. protection of this industry by appealing to such externalities. It is important to emphasize, though, that if knowledge spillovers in the semiconductor industry are global in scope, then Professor Boskin is *still* right. If American computer manufacturers and software firms can learn from innovation in the Japanese semiconductor sector as easily as they can from innovation in the American semiconductor sector, then one cannot justify protection on the basis of these externalities.

Having distinguished these two types of knowledge spillovers, we can now consider how they might be mediated and how we might find their traces in the data. Obviously, pecuniary spillovers are mediated through actual commercial transactions – one obtains this kind of spillover by buying a new or improved good at less than the "full quality-adjusted price", (in the usage of GRILICHES [1992]) and the amount of spillover will be a function of the frequency and intensity of ones purchases. In linking upstream innovation to the benefits it generates downstream, it will be necessary to find or construct an "input-output" matrix or some other mapping of the pattern of input purchases across sectors. In fact, SCHERER [1982] and others have made quite ambitious attempts to use such matrices to construct measures of the rate of return to R&D, taking account of the fact that much of the benefit leaks downstream.

It is doubtful, though, that the pattern of propagation of knowledge spillovers is the same as the pattern of propagation of pecuniary spillovers. Certainly, we would not expect the pattern of knowledge spillovers to be necessarily proportional to the pattern of commercial transactions between firms and sectors. On an annual basis, professors of economics generally spend far more on health care, housing services, and automobile maintenance than they do on subscriptions to economics journals. Yet, if they are at all like me, they have learned comparatively little from their doctors, landlords, or mechanics, relative to the knowledge spillovers they receive from the economic research of other scholars. To cite a more serious example from GRILICHES's [1992] survey, "the photographic equipment industry and the scientific instruments industry may not buy much from each other but may be, in a sense, working on similar things and hence benefiting much from each other's research". At the firm level, the most intense knowledge spillovers may be those which take place between direct competitors who buy nothing from one another [9].

9. This is not meant to imply that knowledge spillovers cannot occur between upstream and downstream firms or industries or that the pattern of knowledge spillovers is always orthogonal to the pattern of commercial transactions.

If knowledge spillovers are the primary phenomena of interest, and theory strongly suggests that they are, then the search for them would seem to require a measure of "proximity" in technology space [10]. In turn, obtaining a reasonable measure of proximity in technology space will require us to do empirical work at a level that is much more disaggregated then the level at which most of the empirical work on international R&D spillovers has been done, because there is enormous technological heterogeneity across and even within industries. This point can be made in a simple way with an example from my 1996 working paper: "For instance, a maker of industrial solvents is unlikely to directly benefit from the research of pharmaceuticals companies on psychoactive drugs, even though both are in the "chemical" industry... If we find no relationship between the productivity of our industrial solvent manufacturer and research and development by the pharmaceuticals manufacturer, that does not mean there are no knowledge spillovers. On the other hand, if we find a relationship, it is difficult to give it a causal interpretation. We are more likely observing common demand or input price shocks or a common time trend than actual spillovers [11]."

Distilling "real" knowledge spillover effects from potentially spurious correlation of this kind requires a measure of technological proximity by which to weight "external" R&D, domestic and foreign. Such a measure can only be obtained by using data at the level of the producer which provides a rich description of the R&D activities of individual firms and the distribution of that effort across different technological fields. Such data exist, and I will argue consistently throughout this survey that we have little chance of obtaining good estimates of knowledge spillovers without using them.

Before we leave our taxonomy of spillovers, I will touch on a completely different topic – what might be called "market access spillovers", a term taken from the survey by BLOMSTROM and KOKKO [1996] though some of these ideas have also been explored at length by James RAUCH [1996] and by AITKEN, HARRISON, and HANSON [1994]. If foreign consumers have imperfect information about the quality of indigenous producers, then welfare improving trade may not take place simply due to lack of information. This is Akerlof's "lemons problem" on a global scale [12]. Once

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10. A referee has suggested that where both pecuniary and knowledge spillovers are present, it may be difficult to distinguish between them. This is likely to be true. One way around this problem is to rely on indices of innovation, such as patents, that are less affected by input cost shocks then are revenue-based indices like TFP. Furthermore, since knowledge spillovers are likely proportionate to *technological proximity* rather than proximity in transactions space, the availability of data on technological proximity can also help researchers distinguish between the two effects.

11. Professor F.M. SCHERER and others have pointed out to me that problem is exacerbated by the way R&D data is collected in some countries. In the U.S., R&D expenditure data is collected from firms. Then, these sums are assigned to the single industry identified as its "primary" industry. For diversified firms, which do a large fraction of private sector R&D in the U.S., this can lead to severe measurement problems. GRILICHES [1992] also notes this point.

12. See AKERLOF [1970].

a sufficient number of purchases have taken place, especially if foreign consumers learn from watching other foreign consumers behavior, the prior expectation of the distribution of quality among foreign producers may be updated such that foreign consumers suddenly demand the products of indigenous producers. Indigenous producers (and foreign consumers) can benefit from "reputation spillovers" of this kind. Likewise, indigenous producers may learn about the feasibility of exporting to certain foreign markets (and the potential profits from doing so) by observing the export activities of other indigenous producers. If international trade and investment can be described by a search model with a reasonably high search cost, then these kinds of information spillovers may be quite important [13]. However, they are not knowledge spillovers. Furthermore, it is not clear that these information spillovers will generate anything other than one-time gains from the advent of mutually advantageous trade. They will not drive endogenous growth. Thus we will not consider them further in this survey.

4 Empirical Methods for Measuring International R&D Spillovers

Up to now, most empirical papers on international R&D spillovers have used either production functions of some kind or the dual of the production function, a cost function. Both empirical models have their pitfalls, as a generation of work within the microproductivity research community has demonstrated. Here, I only summarize the rich and eminently readable discussions found in GRILICHES [1992] and in GRILICHES and MAIRESSE [1995]. In the case of the production function, the basic method is to model output as a function of labor, physical capital, and knowledge capital such that

$$Q = C^{\alpha} L^{\beta} K^{\gamma} e^{\varphi}$$

where Q is output, C is physical capital, L is labor, K is "knowledge capital", and the φ represents a set of controls for industry and time effects [14]. It is worth pointing out that the theory of production undergirding this model is specified at the level of the *firm*. Typically, firm level data

13. See the paper by KINOSHITA and MODY [1996] for a development of these ideas with respect to foreign direct investment and empirical work using data on Japanese FDI in Asia.
14. This is a simple "Cobb-Douglas" production function. Of course, one can estimate more complicated functional forms, such as the translog. However, if measurement error is a substantial problem, then the interpretation of the coefficients on higher-order terms becomes especially problematic.

is hard to come by, and in the empirical literature on international R&D spillovers production functions are often run on aggregated industry or even national-level data. This presents a number of conceptual problems. It is one thing to assume that a firm maximizes output given a vector of prices. It is quite another thing to imagine that an industry or a nation undertakes a similar maximization across multiple distinct product markets. Under a number of rather stringent assumptions, of course, researchers can treat an industry or a country as a single firm, but such assumptions generally do not do justice to the observed heterogeneity of individual producers.

In any case, the production function approach generally treats knowledge capital, or R&D capital, in a way symmetric to that of physical capital [15]. Taking the logs of both sides of this equation and expressing it in difference form allows us to model output growth as a function of the growth of inputs.

$$\begin{aligned} q_{i,t} - q_{i,t-1} = {} & \alpha\,(c_{i,t} - c_{i,t-1}) + \beta\,(l_{i,t} - l_{i,t-1}) \\ & + \gamma\,(k_{i,t} - k_{i,t-1}) + (\varphi_i - \varphi_i) + u_{i,t} - u_{i,t-1} \end{aligned}$$

This expression is linear in the logs of the variables and has the convenient feature of differencing away "fixed effects". The coefficient on the changes in the knowledge capital stock has the interpretation of the partial effect on output holding other factors constant, which, in turn, is generally interpreted as the relationship between total factor productivity growth and knowledge capital [16].

The manner in which K is constructed will be of particular interest. If there are no R&D spillovers, of course, then K will simply be a "stock" measure constructed, via the perpetual inventory method, from past investments in R&D by only the unit of observation; typically a firm or industry. If there are only intranational R&D spillovers, we might include domestic "external" R&D investments along with "own" R&D investments in the construction of our stock measure. Since some of the external R&D is bound to be more relevant to "own" output then others, we need some weight matrix by which to focus on the relevant external R&D and screen out the rest. As we have reasoned above, the best weight matrix will be some measure of technological proximity between "own" and "other" R&D-performing units. Furthermore, as we have reasoned, this matrix will be most believable if it is constructed at or at least based on information from the firm level. If there are international R&D spillovers, then we must construct a parallel weighted sum of technologically relevant R&D conducted in other countries. Allowing the international and intranational R&D spillover terms to enter symmetrically into the production function,

15. This treatment has itself been criticized by a number of scholars in the micro productivity research community, including NELSON [1988], GRILICHES [1979], and KLETTE [1994].

16. An alternative frequently pursued in the literature is to calculate a "Solow residual" by subtracting from the log of output a Tornqvist index of the log of inputs. The resulting series can be interpreted as TFP, and this can then be regressed on various measures of knowledge capital.

we may have something like

$$
\begin{aligned}
q_{i,t} - q_{i,t-1} = {} & \alpha\,(c_{i,t} - c_{i,t-1}) + \beta\,(l_{i,t} - l_{i,t-1}) + \phi\,(r_{i,t} - r_{i,t-1}) \\
& + \gamma\,(s_{di,t} - s_{di,t-1}) + \rho\,(s_{fi,t} - s_{fi,t-1}) \\
& + (\varphi_i - \varphi_i) + u_{i,t} - u_{i,t-1}
\end{aligned}
$$

so that we have "own" R&D (denoted r) and two kinds of spillovers, domestic (s_d) and foreign (s_f). We can then compare their relevant impact on productivity growth by comparing the coefficients on the two spillover terms.

The construction of the "own" and external knowledge stocks presents a number of conceptual and measurement problems. Leaving aside for the moment the problem of how to construct a measure of technological proximity, we also need a measure of depreciation of knowledge capital and a sense of the lag structure of past internal and past external R&D in terms of its effect on output. There is little firm empirical evidence to guide us here, nor is there any reason to believe that these parameters should remain stable over time or across firms and industries. It is therefore likely that the knowledge stocks will be measured with considerable error.

Unfortunately, it is also true that fluctuations in output, controlling for labor and capital (hence, TFP), will be influenced by many things other than cost reducing process innovation or quality-enhancing product innovation. Demand and cost shocks will also be present, as will be shortcomings in the ability of the official price deflators to accurately measure quality change over time. Fluctuations in measured TFP will also be affected by changes in the firms' ability to appropriate the benefits from its innovations, and here the model runs into a major conceptual difficulty. The microfoundations of the neoclassical production function are derived under conditions in which the firm is a price-taker in the output market. Of course, endogenous technological change requires that firms have the incentive to undertake costly research – hence it implies the existence of at least temporary monopoly power at the firm level. If we allow output prices to differ from that which would hold under perfect competition, then we begin to move away from the theoretical microfoundations of the production function [17]. This presents a theoretical problem, and ultimately we will need an empirical model that explicitly and formally takes into account imperfect competition among firms to resolve it [18]. It also presents a practical problem, in that measured TFP varies for reasons that have like to do with innovative effort [19].

An alternative specification is to estimate a "knowledge production function" by using some measure of innovation other than output growth on the left hand side of the equation. One obvious alternative is to use counts

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17. I wish to thank Zvi GRILICHES for raising this point.
18. Zvi GRILICHES and Tor KLETTE [1997] have done research along the lines, developing an empirical analog of the "quality ladder model".
19. For a particularly dramatic example of this, see the Bronwyn HALL's [1994] "Has the Rate of Return Declined?"

of patents as a measure of innovation. Thus, suppressing time subscripts, the regression equation becomes

$$N_i = R_i^{\beta}\, S_{di}^{\gamma_1}\, S_{fi}^{\gamma_2}\, \Phi_i$$

where N is the number of patents obtained by firm i, R is "own" R&D spending, S_d and S_f represent domestic and foreign spillovers, respectively, and $\Phi_i = e^{\Sigma\, \delta_c\, D_{ic}}\, e^{\varepsilon_i}$, a set of controls for industry and time effects, plus an error term.

Patent counts are less likely than deflated sales to be subject to cost and demand shocks. Unfortunately, patent counts have problems of their own as measures of innovation, not the least of which is the fact that most corporate patents are found, *ex post*, to be of little or no economic value. Some progress can be made, potentially, by weighting patent output by the subsequent citations of those patents. Bronwyn Hall is currently pursuing such research with Adam Jaffe and Manuel Trajtenberg.

A seemingly sensible alternative is to estimate a cost function rather than a production function. As GRILICHES [1992] notes, "the advantage of the cost structure approach is that it is often more flexible in functional form used and that it benefits from imposing more structure, considering the impact of R&D not only on total costs but also on the amount of labor and intermediate products used". Like its dual, the production function, it is specified at the level of the firm. Running regressions of cost functions on industry or national data will pose the same conceptual problems as does running production functions on aggregate data. However, the cost function does possess the following advantage over its dual: it can be estimated, in principle, when a firm is not a price-taker in the output market, as long as it is a price taker in the various input markets.

Although a number of different models based on the cost function have been estimated, I describe here the approach taken by Jeffrey Bernstein and a number of co-authors. I summarize his own description, using his notation [20]. Bernstein assumes a production process characterized by

$$y_t = F\,(\nu_t,\, K_t,\, S_{t-1})$$

where y is output, v is the vector of non-capital inputs, K is the vector of capital inputs (physical capital and R&D capital), and S is the vector of spillover variables, both domestic (aggregate domestic R&D spending in all other industries) and foreign (R&D spending in the corresponding foreign industry). Spillover terms are lagged by one period, hence the different subscript.

Producers are assumed to minimize cost. The optimization problem can therefore be split into two stages. In the first stage, output quantity is given and capital stocks are fixed. The cost of non-capital inputs are minimized subject to the production function. The solution to the first stage of the problem yields the variable cost function,

$$c_t^{\nu} = C^{\nu}\,(w_t,\, y_t,\, K_t,\, S_{t-1})$$

20. See BERNSTEIN *et al.* [1994, 1995].

where c^v is variable cost and w is the vector of non-capital input prices. C^v is assumed to be twice continuously differentiable, nondecreasing in w and y, and nonincreasing in K, concave, and homogeneous of degree one in w and convex in K. Applying Shepherd's Lemma, the demands for non-capital factors of production can be retrieved, such that

$$\nu_t = \nabla_w C^\nu (w_t, y_t, K_t, S_{t-1})$$

The non-capital factor demands depend on the non-capital factor prices, output quantity, the capital inputs, and the R&D spillovers. Turning to the second stage, the demands for capital inputs are found by minimizing variable plus capital cost, producing the following equilibrium conditions relating to the capital input demands

$$-\omega_t = \nabla_k C^\nu (w_t, y_t, K_t, S_{t-1})$$

where ω is the vector of capital input prices or rental rates. Capital input demands depend on non-capital input prices, output quantity, R&D spillovers, and capital input prices. The last two equation sets constitute the system of equations that is estimated.

There are a number of disadvantages to this approach. The most important, as noted by Griliches, is that the cost function requires the use of good input price data which varies across our units of observation and over time. This generally does not exist for R&D and physical capital even at the industry level. At the firm level, where the theory of the cost function is actually specified, this kind of data does not exist at all, nor is there generally *firm-specific* information on the costs of intermediate inputs. Furthermore, the use on the right hand side of *ex-post* output, rather than "expected output", has the tendency to produce, in GRILICHES's [1992] words "an unwarranted appearance of economies of scale and is likely to bias upward the own and outside R&D capital coefficients, especially in the absence of any other trend-like terms in the equations". This last problem is explored at some length in GRILICHES and HAUSMAN [1986].

5 A Brief Review of the Received Empirical Literature

• Estimates of Knowledge Spillovers

Certainly, the most widely cited and influential study in the literature on international R&D spillovers so far has been the work by COE and HELPMAN [1995] and the similar paper by COE, HELPMAN, and HOFFMAISTER [1995]. In both papers, the authors calculate TFP residuals for a set of countries, using aggregate data on capital and labor. These TFP residuals are then regressed on aggregate R&D spending and a weighted measure of external R&D spending, where the weights are measures of bilateral trade between the countries. This approach has been criticized on a number of grounds. First, of course, there are the conceptual problems raised with estimating what amounts to a production function with country level data. More importantly, the authors' aggregate approach allows them no way to control for technological heterogeneity across firms, industries, and countries. Thus there is no measure of technological proximity. Third, by using trade-related weights, the authors effectively impose on the data the assumption that trade is the prime vehicle through which spillovers are mediated [21]. Fourth, the authors interpret their regressions as cointegrating regressions and were unable to provide standard errors due to the problems of calculating the asymptotic properties of their estimators in a panel in which the time series data exhibit a unit root and cointegration.

These conceptual and methodological problems notwithstanding, the results Coe and Helpman presented in their 1995 *European Economic Review* article are quite striking, implying that international R&D spillovers, mediated through trade, are significant and strong. If Coe and Helpman are interpreting their results correctly, then international trade is evidently an *extremely* potent channel by which technology spills over across countries [22]. The authors have also received some econometric support from Bangtian CHEN and CHIWHA KAO [1995]. Using their previous research on cointegration in panel data, CHEN and KAO are able to place adjusted standard errors around Coe and Helpman's coefficients, confirming their main result that import-weighted "foreign" R&D spillovers are significantly correlated with domestic productivity levels.

Unfortunately, a recent paper by Wolfgang Keller (KELLER [1996]) casts doubt on the interpretation the authors give to the results in their papers. Keller's approach is very simple. Having obtained the data set used for the original Coe and Helpman paper, he first replicates their initial results. Then, using a "Monte-Carlo" approach, Keller takes the ingenious next step of creating a series of randomly generated bilateral trade relationships and uses these randomly generated trade matrices to create the trade-weighted "foreign" R&D stock. He then reruns the baseline Coe-Helpman regressions of aggregate total factor productivity growth on aggregate national and trade-weighted "foreign" R&D stocks. He replicates this experiment one thousand times for each of the main regression models estimated by Coe and Helpman. He finds that "randomly created bilateral trade shares also give rise to large estimated international R&D spillovers; often, in fact, to larger estimated

21. American University economist Walter PARK [1995] also uses data on OECD countries in his study of international R&D spillovers, but he first disaggregates R&D by source – public or private – then further disaggregates by sector. Park constructs a measure of technological proximity between countries based on similarity in the sectoral allocation of R&D, and uses this measure to weight "external" public and private R&D. Like Coe and Helpman, Park finds evidence of international R&D spillovers.

22. Empirical work by BERNARD and JONES [1996] casts some doubt on the view that trade is an important channel of spillovers. The authors demonstrate that the much-noted convergence in aggregate TFP levels across OECD economies is entirely a function of productivity convergence in the *service* sector. Disaggregating by industry, they show that there has been no tendency toward productivity convergence in manufacturing industries, despite the fact that most international trade takes place in manufactured goods rather than services.

spillover effects which are more precisely estimated than by employing the 'true' bilateral trade shares". As Keller himself modestly notes in the abstract to his paper. "This casts some doubt on the earlier results in the literature". Table 1 and Table 2 compare econometric results of Coe and Helpman, Chen and Kao, and Keller. Table 1 presents the Coe and Helpman "baseline" specification. Table 2 presents what is in some ways Coe and Helpman's preferred specification in that it weights "foreign" R&D stocks by the share of imports in that country's GDP. It also allows for the effect of domestic R&D stocks to be higher for the G7 countries. One can see that in all cases, randomly created trade shares lead to higher estimates of the impact of international R&D spillovers than the use of the actual shares.

TABLE 1

The Impact of Domestic and Foreign R&D Spillovers on Productivity.

Variable	Grossman and Helpman	Chen and Kao	Keller
Domestic R&D	.097 (.009)	.093 (.051)	0.28 (.011)
Foreign R&D	.092 (.016)	.100 (.070)	.157 (.013)

TABLE 2

The Impact of Domestic and Import-weighted Foreign R&D Spillovers on Productivity.

Variable	Grossman and Helpman	Chen and Kao	Keller
Domestic R&D	.078 (.008)	.074 (.036)	0.28 (.011)
G7*Domestic R&D	.156 (.015)	.158 (.098)	
Import-weighted Foreign R&D	.294 (.041)	.310 (.145)	.337 (.030)

Professor Jeffrey Bernstein of Carleton University in Canada has, together with various co-authors, undertaken several studies of international R&D spillovers between the U.S. and Japan and between Canada and various trading partners. These papers all share a common methodology: the "cost function" approach outlined earlier. Interpretation of his findings is clouded by the shortcomings of this approach. First of all, the cost functions are estimated using highly aggregated sectoral level data. The assumption that a firm minimizes cost is, as economic assumptions go, not too difficult to swallow. The assumption that the "chemical industry" minimizes costs across several distinct product markets is harder to defend. Furthermore, Bernstein and his co-authors lack data on R&D "prices" or capital goods prices that vary across sectors. At the aggregate level at which he undertakes his analysis, Bernstein is unable to control for technological heterogeneity within sectors. Typically, Bernstein and his co-authors find evidence of R&D spillovers, though his estimates of the elasticities of R&D spillovers vary widely across sectors and countries. Because of the fundamental differences in econometric specification, it is not really possible to compare these results to those reported in Tables 1 and 2, but some of the estimated spillover effects are quite large. For instance, Bernstein and Mohnen found that R&D spillovers from the United States accounted for more than 50% of Japanese productivity growth in the R&D-intensive sectors, whereas spillovers from Japan accounted for about 15% of US productivity growth [23].

6 New Departures

• The use of Measures of Technological Proximity at the Micro Level

One alternative approach to the problem of estimating international knowledge spillovers is to do analysis at the micro level in a way which explicitly controls for technological distance. I have undertaken precisely this approach in my 1996 working paper, "Are Knowledge Spillovers International or Intranational in Scope?" In summarizing my paper in this section, I borrow liberally from that paper.

It builds on the methodologies suggested by Zvi GRILICHES [1979] and first implemented by Adam JAFFE [1986]. Since Jaffe's paper is a familiar one, I will use his notation and follow his development of the model. The typical firm conducts R&D in a number of technological fields simultaneously. I obtain a measure of a firm's location in "technology space" by measuring the distribution of its R&D effort across various technological fields. Let a firm's R&D program be described by the vector F, where

$$F_i = (f_1 ... f_k) \tag{1}$$

and each of the k elements of F represent the firm's research resources and expertise in the k-th technological area. We can infer from the number

23. While industry-level studies may suffer from potential problems of aggregation bias, firm-level studies will inevitably suffer from potential problems of sample selection bias. Most firm-level studies use data on larger, publicly traded firms for reasons of data availability. It is not clear that the results obtained from such studies apply to the relevant industry or the economy as a whole. So, I do not want to be excessively critical of studies done on more aggregate data. To paraphrase Zvi Griliches, in empirical work, there is also no free lunch.

of patents taken out in different technological areas what the distribution of R&D investment and technological expertise across different technical fields has been.

Like Jaffe, I assume that "the existence of technological spillovers implies that a firm's R&D success is affected by the research activity of its neighbors in technology space" [24]. We can measure the "technological proximity" between two firms by measuring the degree of similarity in their patent portfolios. We can state this more precisely: the "distance" in "technology space" between two firms i and j can be approximated by P_{ij} where P_{ij} is the uncentered correlation coefficient of the F vectors of the two firms, or

$$(2) \qquad P_{ij} = \frac{F_i\,F_j'}{[(F_i\,F_i')\,(F_j\,F_j')]^{1/2}}$$

Other things being equal, firm i will receive more "R&D spillovers" from firm j if firm j is doing a substantial amount of investment in new technologies. Firm i will also receive more R&D spillovers if its research program is very similar to that of firm j. Thus, the total potential pool of intranational R&D spillovers for a firm can be proxied by calculating the weighted sum of the R&D performed by all other firms with the "similarity coefficients" for each pair of firms, P_{ij}, used as weights. More simply, suppressing time subscripts here and in the equations below for expositional convenience, the intranational, or "domestic" spillover pool for the i-th is S_{di}, where S_{di} is

$$(3) \qquad S_{di} = \sum_{i \neq j} P_{ij}\,R_j$$

Here R_j is the R&D spending of the j-th firm (j not equal to i) and P_{ij} is the "similarity coefficient". Similar, the potential international, or "foreign", spillover pool is computed as

$$(4) \qquad S_{fi} = \sum_{i \neq j} P_{ij}\,R_j$$

Where R_j is the R&D of firms based in a foreign country, again weighted by the P_{ij}'s. Assume that innovation is a function of own R&D and external knowledge. Then, the "knowledge production function" for the i-th firm is

$$(5) \qquad n_{it} = \beta\,r_{it} + \gamma_1\,s_{dit} + \gamma_2\,s_{fit} + \sum_c \delta_c\,D_{ic} + \varepsilon_{it}$$

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24. This quote was taken from JAFFE [1986].

Following Jaffe, all variables are expressed in logs. In (5), n_{it} is innovation, r_{it} is the firm's own R&D investment, s_{dit} is the domestic spillover pool, s_{fit} is the international spillover pool, the D's are dummy variables to control for differences in the propensity to generate new knowledge across technological fields (indicated by the subscript c), and ε is an error term [25].

I estimate a number of such knowledge production functions, using both patent counts and total factor productivity growth as indices of innovative output, with panel data on Japanese and U.S. high-technology firms. Because I have panel data, I am able to estimate both random and fixed effects versions of my knowledge production. Table 3 compares my fixed effects results to those of JAFFE [1986]. A number of differences in the results can be noted and explained. In theory, fixed effects models control for the effects of left-out variables (especially unmeasured firm-specific heterogeneity) that change slowly over time. However, this comes at the cost of throwing out the cross-sectional variance, which is typically most of the variation in a firm-level data set. Furthermore, given that both R&D and, to a much greater extent, spillovers are measured with error, fixed effects models can actually worsen the bias arising from measurement error. Nevertheless, they are useful as a strong test of the robustness of ones results.

In interpreting the results, the reader must note that, as JAFFE [1986] has pointed out, "From a purely technological point of view, R&D spillovers constitute an unambiguous positive externality. Unfortunately, we can only observe various economic manifestations of the firm's R&D success. For this reason, the positive technological externality is potentially confounded with a negative effect of other's research due to competition. It is not possible, with available data, to distinguish between these two effects...". To put it more concretely, patents are a tool of appropriation. If technological rivalry with other firms is intense enough, and the scope of intellectual property

TABLE 3

Impact of Spillovers on Innovation as Measured by Firm-Level Patenting Fixed Effects Specification.

Variable	Jaffe (U.S.)	Branstetter (U.S.)	Branstetter (Japan)
Own R&D	.398 (.225)	.246 (.091)	.095 (0.98)
Domestic Spillovers	.179 (.058)	.364 (.532)	.927 (.356)
Interaction Term	.020 (.025)	n.a.	n.a.
Foreign Spillovers	n.a.	–.657 (.402)	.373 (.502)

25. Jaffe includes an interaction term between own and external R&D in his version of (5), reasoning that part of the effect of R&D spillovers may be to improve the productivity of a firm's own R&D.

rights conferred by patents is broad enough, firms may sometimes find themselves competing for a limited pool of available patents – a patent race. Because of this, if actual flows of knowledge are weak or nonexistent, and rivalry is strong, our estimates may be negative even though the underlying technological externality is positive.

Jaffe's results are presented in the second column. Unlike Jaffe, my specification of (5) does not include an interaction term between own and external R&D, but I do allow for international and well as intranational spillovers. My results for U.S. firms in the third column are not that different from Jaffe's, given that I use a much narrower cross-section of firms (209 firms to his 432) and a time period that is more than a decade later. I estimate larger intranational spillover effects, but they are estimated with less precision such that they fall below conventional significance levels; The truly new result is the estimated impact of Japanese R&D – it is not significantly different from zero, but the point estimate is negative. I see this as being consistent with anecdotal evidence that U.S. firms are not good at monitoring foreign R&D, whereas Japanese firms were extremely aggressive about patenting in the U.S. Here, a weak positive externality has been "drowned out" by a "patent race" effect. The results presented in the fourth column for Japan are quite different. First, the estimated effect of own R&D is smaller both in magnitude and in statistical significance. In my view, this is primarily a function of measurement error in the Japanese micro-level R&D data, which is more severe than that for U.S. firms. I should also note that in random effects and nonlinear specifications, the elasticity of own R&D is higher and significant. Second, the intranational spillover effect is extremely large and quite significant. Third, the estimated impact of R&D spillovers form American firms is positive, but again, it falls below conventional significance levels. The surprising conclusion that emerges is that R&D spillovers seem to be a predominantly *intranational* phenomenon. This is strikingly different from the results one gets with aggregate data, as seen in Table 2, where innovative output elasticity of "foreign R&D spillovers" is consistently estimated to be higher than that of domestic spillovers, and underscores the importance of working with data at the producer level.

In my 1996 working paper, I estimate linear, random effects, and nonlinear versions of equation 5 with patent counts as the dependent variable. In addition, I use TFP growth as an index of innovative output for both U.S. and Japanese firms. The results are qualitatively similar to those shown here [26]. In most specifications, I can formally reject the hypothesis of equality of intranational and international R&D spillovers. When that is impossible, it is generally because the impact of international R&D spillovers is not significantly different from zero.

26. It is interesting to note that this econometric evidence matches well with survey evidence on where Japanese managers think their "spillovers" come from. When asked in a recent survey undertaken by the Science and Technology Agency of Japan whether, in effect, foreign or domestic sources of spillovers were more important, Japanese R&D managers overwhelmingly cited domestic sources. (This information is based on personal communication with Professor Akira Goto of the Science and Technology Agency.)

• The Use of Patent Citations Data

Of course, my approach has the serious disadvantage of being able to infer the existence of spillovers only indirectly. In principle, at least, a direct measure is available – patent citations. Jaffe and Trajtenberg use this data along with a "citations function" in which the likelihood that any particular patent K granted in year T will cite some particular patent k granted in year t is assumed to be determined by the combination of an exponential process by which knowledge diffuses and a second exponential process by which knowledge becomes obsolete. This relationship is defined as

$$p\,(k,\,K) = \alpha\,(k,\,K)\,\exp\left[-\beta_1\,(k,\,K)\,(T-t)\right]\left[1-\exp\left(-\beta_2\,(T-t)\right)\right]$$

where β_1 determines obsolescence and β_2 diffusion. In their econometric specifications, Jaffe and Trajtenberg are able to derive a nonlinear estimating equation based on this citation function which allows them to predict the probability of citations conditioning on a number of factors, including the nationality of the inventors of both patent k and patent K. Drawing upon an enormous data base of patents taken out in the U.S. by both domestic and foreign inventors and the associated data on citations, JAFFE and TRAJTENBERG [1996] have found that inventors are much more likely to cite previous patents taken out by inventors from their own country than one would expect given the distribution of scientists and research resources across countries. Furthermore, this tendency holds up even after controlling for technological field, cohort effects, and other factors. This finding suggests that R&D spillovers have a very strong "intranational" component. In related work, Francis NARIN [1995] finds similar disproportionately "intranational" citation patterns in his bibliometric study of scientific papers in the biological sciences. The implications of these findings for the global economy are far from clear, but they at least suggest that R&D spillovers may be much more of an *intranational* phenomenon than the estimates embodied in the work of Coe and Helpman suggest. Jaffe and Trajtenberg are currently working on using the direct measures of knowledge spillovers obtainable from this patent citation data base to construct technology flow matrices between industries and countries, which can then be used to measure the impact of international and intranational spillovers on output and productivity.

• From Spillovers to Transfer

Up to this point, this paper has focused on the extent to which research activity in one country contributes to innovation in another. This kind of international technological interaction generally occurs between innovating developed countries at the technological frontier. This is, or arguably should be, a parameter of great interest to policymakers in the small number of advanced countries where most of the world's new technological knowledge is developed, for innovation is the principal means by which these countries can continue to grow.

For the majority of humankind, however, a far more important potential source of growth is not the development of new technologies but the implementation of existing technologies that have already been developed abroad. This is a different kind of phenomenon, and it probably requires a different conceptual framework [27]. Unfortunately, the "new departures" I have outlined here will be of little use in the context of examining technology transfer between developed and developing countries since there is little or no observable "innovation" by third world producers (*i.e.*, no independent patenting by the recipients of the transfer). As a result, I will have to leave consideration of this very important issue for another time.

7 Conclusion

I began this survey by reviewing the theoretical models that have highlighted the importance of international knowledge spillovers. I then pointed out that the knowledge spillovers highlighted in the theoretical literature can be distinguished conceptually, and possibly empirically, from "pecuniary spillovers". I further reasoned that identifying the traces of knowledge spillovers in the data requires a measure of technological proximity between firms. Given the enormous technological heterogeneity within, say, 3-digit industries, obtaining such a measure requires that researchers undertake their analyses at a very disaggregated level. I have argued that the most appropriate level of aggregation is the micro level [28].

From there, I reviewed some well-known empirical studies, pointing out various weaknesses in each, including the failure to control for technological proximity. Finally, I reviewed two alternative approaches to the measurement of knowledge spillovers. I pointed out, though, that these methodologies will be of limited usefulness in exploring the important question of how and to what extent first-world technology is being transferred to developing countries.

Theorists have shown that the presence of knowledge spillovers may matter a lot for trade theory and the traditional policy prescriptions that have flowed form it. Ultimately, though, the significance of these theories will be, and rightly should be, determined by empirical evidence. This survey shows that confronting these theories with data is not easy, and that we have made limited progress so far. However, I also hope that I have demonstrated that there are data and modeling tools at hand which may allow us to push forward. It is my hope that at least some readers will be persuaded to contribute to this effort. Grossman and Helpman and others have raised some very important questions. Now, we need answers.

27. Grossman and Helpman give this sort of technology transfer entirely separate treatment in their landmark book (Grossman and Helpman [1991]).

28. I acknowledge again, however, the "sample selection" issues that are likely to arise with the use of micro-level data.

● References

Aitken, Brian, Hanson, G., Harrison, A. (1994). – “Spillovers, Foreign Investment, and Export Behavior”, *NBER Working Paper No. 4967.*

Akerlof, G. (1970). – “The Market for ‘Lemons’: Quality Uncertainty and the Market Mechanism”, *Quarterly Journal of Economics*, 84(3).

Andrew, B., Jones, C. (1996). – “Comparing Apples to Oranges: Productivity Convergence Across Countries and Industries”, *American Economic Review,* December 1996.

Bernstein, J., Mohnen, P. (1994). – “International R&D Spillovers Between U.S. and Japanese R&D Intensive Sectors”, *National Bureau of Economic Research Working Paper 4682*.

Bernstein, J., Yan, X. (1995). – “International R&D Spillovers Between Canadian and Japanese Industries”, *NBER Working Paper 5401.*

Blomstrom, M., Kokko, A. (1996). – “Multinational Corporations and Spillovers”, *National Bureau of Economic Research Working Paper.*

Blundell, R., Griffith, R., Van Reenan, J. (1994). – “Dynamic Count Data Models of Technological Innovation”, *mimeo*, ESRC Center for Microeconomic Analysis of Fiscal Policy.

Caballero, R., Jaffe, A. (1994). – “How High Are the Giants’ Shoulders?” in *1994 Macroeconomics Annual,* National Bureau of Economic Research.

Bangtian, C., Kao, Ch. (1995). – “International R&D Spillovers Revisited: An Application of Panel Data with Cointegration”, Department of Economics and Center for Policy Research, Syracuse University, *mimeo*.

Coe, D., Helpman, E. (1995). – “International R&D Spillovers”, *European Economic Review,* 39(5).

Coe, D., Helpman, E., Hoffmaister, A. (1995). – “North-South R&D Spillovers”, *NBER Working Paper*.

Cohen, W., Levinthal, D. (1989). – “Innovation and Learning: The Two Faces of R&D”, *The Economic Journal, No. 99*.

Ethier, W. (1982). – “National and International Returns to Scale in the Modern Theory of International Trade”, *American Economic Review*, 72, pp. 389-405.

Feenstra, R. (1992). – “How Costly is Protectionism?” *Journal of Economic Perspectives,* Vol. 6, No. 6.

Feenstra, R. (1996). – “Trade and Uneven Growth”, *Journal of Development Economics,* February.

Goto, A. (1993). – *Nihon no Gijutsu Kakushin to Sangyo Soshiki* (Japan’s Technological Progress and Industrial Organization), Tokyo: University of Tokyo Press.

Griliches, Z. ed. (1984). – *R&D, Patents, and Productivity,* Chicago: University of Chicago Press.

Griliches, Z. (1979). – “Issues in Assessing the Contribution of R&D to Productivity Growth”, *Bell Journal of Economics*, 10 (1), pp. 92-116.

Griliches, Z. (1992). – “The Search for R&D Spillovers”, *Scandinavian Journal of Economics,* 94, Supplement, pp. 29-47.

Griliches, Z., Hausman, J. (1986). – “Errors in Variables in Panel Data”, *Journal of Econometrics,* 41 (1), pp. 93-118.

Griliches, Z., Mairesse, J. (1995). – “Production Functions – the Search for Identification”, *NBER Working Paper.*

Griliches, Z., Klette, T. (1997). – “Empirical Patterns of Firm Growth and R&D Investment: A Quality Ladder Model Interpretation”, *NBER Working paper #5945*.

Grossman, G., Helpman, El. (1990). – “Comparative Advantage and Long-Run Growth”, *American Economic Review,* vol. 80, No. 4.

GROSSMAN, G., HELPMAN, El. (1991). – Innovation and Growth in the Global Economy, Cambridge: *The MIT Press.*

GROSSMAN, G., HELPMAN, El. (1995). – "Technology and Trade", in *Handbook of International Economics,* vol. 3, edited by Gene Grossman and Kenneth Rogoff.

HALL, B., GRILICHES, Z., HAUSMAN, J. (1986). – "Patents and R&D – Is There a Lag?" *International Economic Review,* 27, pp. 265-283.

HALL, B. (1993). – "Has the Rate of Return Declined?" *The Brookings Papers on Economic Activity,* vol. 2: Microeconomics.

HAUSMAN, J., HALL, B., GRILICHES, Z. (1984). – "Econometric Models for Count Data with an Application to the Patents-R&D Rerlationship", *Econometrica*, 52, 4.

FUMIO, H., INOUYE, T. (1991). – "The Relationship Between Firm Growth and Q with Multiple Capital Goods: Theory and Evidence from Panel Data on Japanese Firm", *Econometrica,* 59(3).

ELHANAN, H., KRUGMAN, P. (1985). – *Market Structure and Foreign Trade: Increasing Returns Imperfect Competition, and the International Economy,* (Cambridge, MIT Press).

ELHANAN, H., KRUGMAN, P. (1989). – *Trade Policy and Market Structure,* (Cambridge, MIT Press).

IRWIN, D., KLENOW, P. (1994). – "Learning by Doing Spillovers in the Semiconductor Industry", *Journal of Political Economy,* 102 (6).

JAFFE, A (1986). – "Technological Opportunity and Spillover of R&D: Evidence from Firms' Patents, Profits, and Market Value", *American Economic Review,* 76, pp. 984-1001.

JAFFE, A., TRAJTENBERG, M., HENDERSON, R. (1993). – "Geographic Localization of Knowledge Spilloversas Evidenced by Patent Citations", *Quarterly Journal of Economics,* 108 (3).

JAFFE, A., TRAJTENBERG, M. (1996). – "Flows of Knowledge Spillovers", working paper presented at the Strasbourg Conference on the Economics and Econometrics of Innovation.

JONES, C. (1995). – "R&D-Based Models of Economic Growth", *Journal of Political Economy,* vol. 103, No. 4.

KELLER, W. (1995). – "International R&D Spillover and Intersectoral Trade Flows: Do They Match?", *Yale University manuscript.*

KELLER, W. (1996). – "Absorptive Capacity", *Journal of Development Economics*.

KELLER, W. (1996). – "Are International R&D Spillovers Trade-related? Analyzing Spillovers among Randomly Matched Trade Partners", *working paper*, UW-Madison, Department of Economics.

YUKO, K., MODY, As. (1996). – "Private and Public Information for Foreign Investment Decision", *Working paper.*

KLETTE, Tor Jacob (1994). – "R&D, Scope Economies, and Company Structure: A 'Not-so-Fixed-Effect' Model of Plant Performance", *Statistics Norway Research Department mimeo.*

KRUGMAN, P. (1984). – "Import Protection as Export Promotion: International Competition in the Presence of Oligopoly and Economies of Scale", in Henryk Kierzhowski, ed., *Monopolistic Competition and Foreign Trade,* (Clarendon Press).

KRUGMAN, P. (1987). – "The Narrow Moving Band, the Dutch Disease, and the Competitive COnsequences of Mrs. Thatcher: Notes on Trade in the Presence of Dynamics Scale Economies", *Journal of Development Economics,* 27, pp. 41-55.

KRUGMAN, P. (1990). – *The Age of Diminished Expectations,* (Cambridge, The MIT Press).

KRUGMAN, P. (1992). – *Rethinking International Trade,* (Cambridge, The MIT Press).

KRUGMAN, P. ed. (1986). – *Strategic Trade Policy and the New International Economics,* (Cambridge, The MIT Press).

KEUN, K., SCHERER, F. M. (1992). – "Reactions to High-Tech Import Competition", *The Review of Economics and Statistics,* pp. 202-212.

LEVIN, R. D. *et al.* (1987). – "Appropriating the Returns from Industrial Research and Development", *Brooking Papers on Economic Activity,* Vol. 3, pp. 783-820

LIEBERMAN, M. (1984). – "The Learning Curve and Pricing in the Chemical Processing Industries", *Rand Journal of Economics.*

MANSFIELD, E. (1985). – "How Rapidly Does New Industrial Technology Leak Out?" *Journal of Industrial Economics,* 34, pp. 217-223.

MONTALVO, J., YAFEH, Y. (1994). – "A Micro-Econometric Analysis of Technology Transfer: The Case of Licensing Agreements of Japanese Firms", *International Journal of Industrial Organization,* Vol. 12, No. 2.

NADIRI, M. I. (1993). – "Innovations and Technological Spillovers", *NBER Working Paper No. 4423.*

NELSON, R. (1988). – "Modelling the Connections in the Cross Section Between Technical Progress and R&D Intensity", *Rand Journal of Economics,* 19, pp. 478-85.

HIROYUKI, O. (1983). – "R&D Expenditures, Royalty Payments, and Sales Growth in Japanese Manufacturing Corporations", *The Journal of Industrial Economics,* Vol. XXXII, No. 1.

PARK, W. (1995). – "International R&D Spillovers and OECD Economic Growth", *Economic Inquiry,* Vol. 23, No. 4.

RAUCH, J. (1995). – "Search Costs in International Trade", *NBER Working Paper.*

RIVERA-BATIZ, L., ROMER, P. (1991). – "Economic Integration and Endogenous Growth", *Quarterly Journal of Economics,* Vol. 56, pp. 531-555.

ROMER, P. (1990). – "Endogenous Technical Change", *Journal of Political Economy,* 98, S71-S102.

SCHERER, F. M. (1982). – "Interindustry Technology Flows and Productivity Growth", *Review of Economics and Statistics,* LXIV, pp. 627-634.

Science and Technology Agency, Government of Japan (1991), *Gijutsu Yoran (Technology Indicators*).

SPENCE, A. Michael (1984). – "Cost Reduction, Competition, and Industry Performance", *Econometrica,* 50, pp. 483-499.

TEECE, D. (1976). – *The Multinational Corporation and the Resource Cost of Technology Transfer,* (Cambridge, MA, Ballinger Publishing Company).

TREFLER, D. (1993). – "International Factor Price Differences: Leontief Was Right!", *Journal of Political Economy,* vol. 101, No. 6.

TREFLER, D. (1995). – "The Case of the Mising Trade and Other Mysteries", *American Economic Review,*

TYSON, Laura D'Andrea (1993). – *Who's Bashing Whom?: Trade Conflict in High-Technology Industries,* Washington: Institute for International Economics.

VERNON, R. ed. (1970). – *The Technology Factor in International Trade,* NBER, distributed by Columbia University Press.

WAKASUGI, R. (1986). – *Gijutsu Kakushin to Kenkyu Kaihatsu no Keizai Bunseki: Nihon no Kigyo Kodo to Sangyo Seisaku* (The Economic Analysis of Research and Development and Technological Progress: Japanese Firm Activity and Industrial Policy), Tokyo: Toyo Keizai Shimposha.

YOUNG, A. (1991). – "Learning by Doing and the Dynamic Effects of International Trade", *Quarterly Journal of Economics,* 106, pp. 369-406.