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11 The Search for R&D Spillovers

11.1

The recent reawakening of interest in increasing returns and R&D externalities, as in e.g. Benhabib and Jovanovic (1991), Romer (1990) and Sala-i-Martin (1990), provides the motivation for a review of the empirical literature on this topic to see what is known about the actual magnitude of such effects. The "New" growth economics has reemphasized two points: (i) technical change is the result of conscious economic investments and explicit decisions by many different economic units, and (ii) unless there are significant externalities, spillovers, or other sources of social increasing returns, it is unlikely that economic growth can proceed at a constant, undiminished rate into the future. The first observation is not new. It has been articulated by Griliches (1957, 1958 and 1964), Mansfield (1968), Schmookler (1966), Schultz (1954) and many others. The second point, the importance of externalities for growth theory and for the explanation of productivity growth, is the driving force behind the research effort to be surveyed here. Whether R&D spillovers will allow us to escape the fate of diminishing returns depends on their empirical magnitude, which is indeed the topic of this paper. Before we turn to it, however, we need to make a brief detour into taxonomy.

Both publicly supported and privately funded R&D produces ideas and information about new materials or compounds, about new ways of arranging or using them, and about new ways of designing new goods or services for the satisfaction of potential wants of consumers and producers. Often the idea or

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I have benefited (received spillovers?) from reading and re-reading other surveys on this topic, especially, Schankerman (1979, Chap. 5), Mohnen (1989), Huffman and Evenson (1991), Mairesse and Mohnen (1990) and Mairesse and Sassenou (1991). This work has been supported by grants from the Bradley and Guggenheim Foundations. An earlier version of this paper was presented at the NBER Conference on Economic Growth at Vail, Colorado, April 1990.

compound is embodied in a new product or range of products. In that case, the social returns to the particular stream of R&D expenditures can be measured by the sum of the producer and consumer surplus generated by it. Consider, for example, the development of hybrid corn seeds in the public agricultural research sector. If the seed is supplied to agriculture at marginal production cost and the official input price indexes do not adjust for such a "quality" change, then the product of this research will appear as part of the measured productivity growth in agriculture. If the seed is produced by a seed industry but still priced at marginal cost, because of competition there, and the pricing agency adjusts for this quality change, showing a decline in the "real" price of equivalent quality seed, then the product of this research will appear in the hybrid seed industry, rather than in agriculture per se. If the hybrid seed industry has some monopoly power which is competed away slowly and the price indexes do not register this as a quality change, the gain from this innovation will be divided, with shifting shares between both industries. To the extent that the new product is sold directly to consumers and the CPI components are not adjusted for the associate "quality" changes, as may be the case with certain drugs or personal computers bought by the household sector directly, the social "product" of the associated research may be missed entirely.

These examples are intended to illustrate that to the extent that a particular innovation is embodied in a product or service, its social product is computable in principle. How it actually will show up in our national product accounts will depend on the competitive structure of the industry and the ingenuity and energy of the "price" reporting agencies. In principle, a complete hedonic calculation would produce the right prices in the right industry and would allow us to attribute productivity growth where it actually occurred. Its influence in downstream industries could then be viewed as just another response to declining real factor prices, a "pecuniary" externality, one that is relatively familiar and easy to deal with.

The more difficult to measure and the possibly more interesting and pervasive aspect of R&D externalities is the impact of the discovered ideas or compounds on the productivity of the research endeavors of others.[1] This is a nonpecuniary externality which is not embodied in a particular service or product, though it might be conveyed by a printed article or a news release. It has the classic aspect of a nonrivalrous good and it is usually very hard to appropriate more than a tiny fraction of its social returns. Even if it were possible to establish some property rights in the idea (e.g. via patents), the resulting second-best prices would be nonlinear and would not provide us with appropriate measures of either marginal or total social returns. To measure them directly in some fashion, one has to assume either that their benefits are localized in a particular industry or range of products or that there are other ways of identi-

1. The distinction between the previous case and this one is related to Meade's (1952) distinction between "unpaid factors" and atmosphere.

fying the relevant channels of influence, that one can detect the path of the spillovers in the sands of the data.

There are other public goods which raise somewhat similar measurement problems: the provision of roads to the motor transport industry, of airports and flight controllers to the airlines, and of security services to private businesses. All of these have certain aspects of increasing returns to them but are also subject eventually to congestion in use and hence reasonable pricing schemes are feasible in principle. The education sector is possibly somewhere in between, providing both a private product which could be better priced and knowledge externalities, both in the small and in the large. Here I limit myself primarily to a discussion of the work on R&D spillovers though some of the issues discussed apply also to attempts to estimate other kinds of externalities.

11.2

There are basically two types of estimates to be found in the literature: estimates of social returns to a particular well-identified innovation or a class of innovations whose effects are limited to a particular industry or sector and can be measured there; and regression-based estimates of overall returns to a particular stream of "outside" R&D expenditures, outside the firm or sector in question. Most of the earlier work in either vein was devoted to measurement of social returns to public investments in agricultural research. This reflected, in part, the greater availability of agricultural data and, also, the more advanced state of applied econometric research in agricultural economics in the 1950s and early 1960s.[2]

Perhaps the earliest attempt to compute something like a social rate of return (actually a benefit-cost ratio) to public R&D appears in Schultz's (1954) book where, after having computed an index of total factor productivity growth for U.S. agriculture, he estimates the amount of resources saved by the technological change that occurred and compares it to the total public investments in agricultural research and finds it to have been a good investment.

This computation, I thought, could be improved by putting it explicitly within the consumer surplus framework. Using data collected for my Ph.D. thesis on the average yield improvement brought on by the use of hybrid seed, from a variety of experimental and observational data, detailed data on the cost of hybrid corn research collected from various agricultural experiment stations, and an estimate of the price elasticity of demand for corn from the existing agricultural economics literature, I computed current and future consumer surplus flows, discounted them back to the present, and compared them to the cumulated research cost; see Griliches (1958). The resulting benefit-cost ratio of about 7 was interpreted, wrongly, as implying a 700 percent rate of

2. See Griliches (1979), Norton and Davis (1981), Mairesse and Mohnen (1990) and Huffman and Evenson (1991) for reviews and additional references.

return to public investments in hybrid corn research. The associated internal rate of return was on the order of 40 percent, still very high, but it was the first number that got the most publicity and I did little to correct the record on this. In the same paper, similar computations were made using Schultz's numbers for total agricultural research and my own more sketchy numbers on the potential social returns to hybrid sorghum research.

In the work that followed, improvements were made in both the approximation formula for consumer surplus and the range of data used for the computation. Some major examples of subsequent work in agriculture were Peterson's (1967) estimate of returns to poultry breeding research, Barletta's (1971) estimate of the returns to corn breeding research in Mexico, and the Schmitz and Seckler (1970) estimate of returns to the tomato harvester. Weisbrod (1971) used a similar approach to estimate the social return to poliomyelitis research. Probably the most elaborate and impressive application of such ideas was in the work of Mansfield et al. (1977a). It is also the only set of case studies available for manufacturing innovations. In computing social returns, they tried to take into account also the research expenditures of related unsuccessful innovators and the losses in rents incurred by competitors. The median social rate of return for the 17 innovations they examined was 56 percent, somewhat more than double the comparable median private rate of return of 25 percent. Bresnahan's (1986) study of computer industry spillovers to the financial sector is also an extension of this general approach. He uses the estimated decline in "real" computer prices from earlier studies by Knight and Chow and an assumed elasticity of derived demand for computers by the financial services sector to compute the implied total welfare gains from such spillovers. Trajtenberg's (1990) estimates of welfare gains from CT scanners is based on a much more elaborate and estimated model, but could also be viewed as a descendent from this line of research.

11.3

Such case studies suffer from the objection that they are not "representative," that they have concentrated on the calculation of social rates of returns or spillovers only for "successful" inventions or fields. They are also much more difficult to do, requiring usually significant data collection, familiarity with the topic or event being analyzed and expose one, potentially, to criticism by those who actually know something about the subject. For these reasons, especially the desire to be more general and inclusive, and because of the growing availability of computer resources, much of the recent work has shifted to regression-based studies. Measures of output or TFP or of their rates of growth, across firms or industries, are related to measures of R&D "capital" or the intensity of R&D investment (R&D to sales or value-added ratios). A subset of such studies also includes measures of "outside" or "borrowable"

R&D capital in an attempt to estimate the contribution of spillovers to the growth in productivity.

Again, both the earliest and some of the most sophisticated studies of this topic have been done in agriculture. The first regression study, Griliches (1964), used the difference in agricultural outputs and inputs across states in the U.S. in three different time periods (1949, 1954 and 1959) and included in the "production function," among other variables, a measure of public expenditures on agricultural research, which differed from state to state and over time. The resulting elasticity estimate was on the order of 0.06, implying the rather high social rate of return of $13 per year (at the average farm level) for each dollar of public investments in research in agriculture. A number of other studies, e.g. Evenson (1968) and Huffman and Evenson (1991), improved on the original study in many respects, first by exploring more complicated lag functions in the construction of the public R&D variable, but second, and more importantly, by raising the question and facing up to the possibility of geographic spillovers, the fact that Iowa research may also have an effect on agricultural productivity in Nebraska.

Regression-based studies raise problems of their own. The main set of issues revolves around the question of how output is measured and whether the available measures actually capture the contribution of R&D (direct or spilled-over), and how R&D "capital" is to be constructed, deflated and depreciated. Since I have discussed these issues at some length in Griliches (1979 and 1988), I focus here only on issues raised by the attempt to measure spillovers.

11.4

The notion of externalities as a source of increasing returns and productivity growth has a long history in economics. Originally it was based on gains from specialization, from the development of "know-how," and on the interaction of craftsmen and engineers. The idea of reconciling competitive equilibrium with increasing returns by modeling the individual firm production (or cost) function as depending, parametrically, on industry aggregate activity variables (output or capital) goes back to Edgeworth and before; see Chipman (1965 and 1978) for surveys of the earlier literature. Explicit algebraic formulations appear in Simon (1947), Meade (1952), Chipman (1978), Arrow (1962) and Sheshinski (1967). In the latter papers the externality arises from "learning by doing" and is proxied by the size of the capital stock. I came across this kind of formulation first in an unpublished note by Grunfeld and Levhari (1962) and applied it to R&D in Griliches (1979).

In that version, the level of productivity achieved by one firm or industry depends not only on its own research efforts but also on the level of the pool of general knowledge accessible to it. Looking at a cross section of firms within a particular industry, such effects cannot be distinguished. If the pools of knowledge differ for different industries or areas, some of it could be deduced from interindustry comparisons over time and space. Moreover, the productivity of own research is affected by the size of the pool or pools it can draw upon. This leads to a formulation in which there is an interaction between the size of individual and aggregate research and development efforts.

A simple model of within-industry spillover effects is given by

$$Y_i = BX_i^{1-\gamma}K_i^{\gamma}K_a^{\mu},$$

where Y_i is the output of the ith firm which depends on the level of conventional inputs X_i, its specific knowledge capital K_i, and on the state of aggregate knowledge in this industry K_a. Note that constant returns are assumed in the firm's own inputs, X_i and K_i. This simplifies the example greatly. Assuming also that the aggregate level of knowledge capital $K_a = \sum_i K_i$ is simply the sum of all specific firm research and development capital levels and that own resources are allocated optimally and all firms in the industry face the same relative factor prices, then the individual K_i to X_i ratios will be given by

$$\frac{K_i}{X_i} = \frac{\gamma}{1-\gamma}\frac{P_x}{P_k} = r,$$

where P_x and P_k are the prices of X and K, respectively, and r, the K/X ratio, does not depend on i. The individual production functions can then be aggregated to yield:

$$\sum_i Y_i = \sum_i BX_i(K_i/X_i)^{\gamma}K_a^{\mu} = \sum_i BX_i r^{\gamma}K_a^{\mu} = Br^{\gamma}K_a^{\mu}\sum_i X_i .$$

Since the K_i/X_i ratios are all equal to r, so also is $\sum K_i/\sum X_i$, which we can substitute back into this equation, yielding:

$$\sum_i Y_i = B\left(\sum_i K_i \Big/ \sum_i X_i\right)^{\gamma} K^{\mu}\sum_i X_i = BX_a^{1-\gamma}K_a^{\mu+\gamma} .$$

Here, $X_a = \sum_i X_i$, $K_a = \sum_i K_i$, and the coefficient of aggregate knowledge capital is higher ($\gamma + \mu$) than at the micro level (γ only), reflecting at the aggregate level not only the private but also the social returns to research and development, thereby providing a framework for reconciling the results from micro and macro based R&D studies.

Of course, this formulation is rather simplistic and is based on a whole string of untenable assumptions, the major ones being: constant returns to scale with respect to X_i and K_i and common factor prices for all firms within an industry. These assumptions could be relaxed. This would add a number of "mix" terms to the equation, indicating how aggregate productivity would shift if the share of, say, the larger firms, were to increase (in the case of economies of scale). If the mix of firms and/or the firm specific prices stay stable then the above formula remains a reasonable approximation to a more complicated underlying reality.

The problem is much more complicated when we realize that we do not not deal with one closed industry, but with a whole array of firms and industries which "borrow" different amounts of knowledge from different sources according to their economic and technological distance from them; see Kislev and Evenson (1975, Chap. 4). The relevant concept of "distance" is very hard to define empirically. If we return to our previous example and now interpret the index i as referring to industries rather than firms, it makes little sense to define K_a as $\sum_i K_i$. Rather

$$K_{ai} = \sum w_{ij} K_j$$

is the amount of aggregate knowledge borrowed by the ith industry from all available sources. K_j measures the levels available in these sources, while w_{ij}, the "weighting" function, can be interpreted as the effective fraction of knowledge in j borrowed by industry i. Presumably w becomes smaller as the "distance," in some sense, between i and j increases. Thus we need an additional distributed (lag) over space function to construct a measure of the stock of borrowed knowledge.

What should such a weighting function be based on? Earlier suggestions were based on "vertical" borrowing; Brown and Conrad (1967) used the input-output table to measure the "closeness" of industries proportional to their purchases from each other, while Terleckyj (1974) used the capital and intermediate inputs purchases matrix weights, assuming that "borrowed" R&D is embodied in purchased inputs. Raines (1968) used the "horizontal" product field classification of NSF to include as inputs also the R&D expenditures of other industries which were reported as belonging to its product field. More recent examples of these approaches can be found in Terleckyj (1980), Wolf and Nadiri (1987) and partially in Sterlacchini (1989).

Actually, as noted in the introduction, there are two distinct notions of R&D "spillovers" here which are often confused in the literature. In the first, R&D intensive inputs are purchased from other industries at less than their full "quality" price. This is a problem of measuring capital equipment, materials and their prices correctly and not really a case of pure knowledge spillovers. If capital equipment purchase price indices reflected fully the improvements in their quality, i.e., were based on hedonic calculations, there would be no need to deal with it. As currently measured, however, total factor productivity in industry i is affected not only by its own R&D but also by productivity improvements in industry j to the extent of its purchases from that industry and to the extent that the improvements in j have not been appropriated by its producers and/or have not been incorporated in the official price indices of that (i) industry by the relevant statistical agencies. The use of purchase flow weighted R&D measures assumes that social returns in industry j are proportional to its R&D investment levels and that the amount of such returns transferred to industry i is proportional to its purchases from industry j.

A good example of such productivity transfers would be the computer industry. It has had a tremendous real productivity growth, though most of it, until recently, was unmeasured in the official indices, and unappropriated within the industry itself (because of rather intensive competitive pressures). Different industries have benefited differentially from it, depending on their rate of computer purchases. One way of accounting for it would be to adjust upward the relevant capital equipment figures by their computer content; see Berndt and Morrison (1991) and Siegel and Griliches (1992) for recent attempts along this line. The alternative is to "import" the computer industry's R&D in proportion to an industry's purchases from it.

But these are not real knowledge spillovers. They are just consequences of conventional measurement problems. True spillovers are ideas borrowed by research teams of industry i from the research results of industry j. It is not clear that this kind of borrowing is particularly related to input purchase flows. 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. One could argue that this is what the SIC classification is for. Presumably, the usefulness of somebody else's research to you is highest if he is in the same four-digit SIC classification as you are; it is still high if he is in the same three-digit industry group; and, while lower than before, the results of research by a firm in your own two-digit classification (but not three-digit) are more likely to be valuable to you than the average results of research outside of it. The problem arises when we want to extend this notion across other two-digit industries. Here there is no natural order of closeness (e.g. is "leather" closer to "food" or to "textiles"?). The situation is complicated further by the fact that micro R&D data are collected from firms rather than establishments and that major R&D performers are conglomerates, spanning several four-, three- and even two-digit SIC classifications. The NSF's applied R&D by product field data help a little, but not enough. Ideally, such data should be collected at the business-unit level. Unfortunately, the FTC stopped collecting within-firm product line R&D data in 1977.

There are two possible approaches to the construction of "spillover" stocks or "pools": (i) a symmetric approach, where every firm in a subindustry is treated equally, and all R&D within the industry or some alternative classification scheme is aggregated with equal weights, and (ii) where every possible pair of firms, industries, or countries is treated separately, and the relevant stock of spillovers for the "receiving" unit is constructed specifically for it, using its "distance" from the various spilling units as a weight.

The first type of construction corresponds to the first formula given above. At the two-digit level, total industry R&D was used as a measure of within-industry spillovers by Bernstein and Nadiri (1989) in analyzing individual firm cost functions. Rather than using the SIC classification as is, one could group three-digit SIC categories into clusters based on a priori notions about the extent of commonality in their technological and scientific base. This is similar to the use of crop-climatic regions by Evenson and Kislev (1973) with all units having equal access to all the research done by others in the same industry or region. In some models, e.g. Schankerman (1979, Chap. 5), the amount borrowed depends also on the level of own research expenditures, allowing thereby for an interaction and potential synergy between the two flows of research expenditures: "inside" and "outside." In the Huffman and Evenson (1991) work there is an effect not only from the research of others within the same climatic region but also an additional spillover, at a lower rate, from neighboring regions.

In the second type of construction, there is a wide choice of possible weights to model what is, essentially, an intellectual-scientific-technological "distance" between firms and industries. Among the various possibilities would be: (1) using the NSF's applied R&D product field by industry table to induce a distance metric, on the assumption that if an industry is doing R&D on some other industry's products, it is in some sense closer to it technologically than if it does not; cf. Raines (1968) and Schankerman (1979); (2) using company industrial diversification data from the Census of Enterprises or Compustat data to compute an alternative measures of closeness in the sales-demand space; see Jaffe (1986); (3) using information on rates of cross referencing of patents across product fields to infer the technological distance between them; (4) using a cross classification of patents, as in Scherer (1982) and Englander et al. (1988), or innovations, as in Robson et al. (1988) and Sterlacchini (1989), by industry of "production" and industry of use, to "flow-thru" R&D expenditures from performing to "using" industries; and (5) using the diversification of a firm's patenting activity across technologically determined patent classes to infer "overlap" and closeness measures for inventive activity, as in Jaffe (1988). In each of these cases one has to assume some simple weighting functions (e.g. influence declining exponentially with the particular concept of distance) or group the data into a few categories: immediate neighborhood, related fields and the rest. There are not enough degrees of freedom or independent variation in such productivity and R&D series to allow one to estimate very complex distributed lag schemes over both time and all the other firms and industries.

Much of the recent work has used patent data to develop measures of the "direction" of spillovers. A major data construction effort was pursued by Scherer (1982, 1984) who classified a large sample of patents by both the industry where the invention occurred and the industry (or industries) where it was expected to have its major impact. Having constructed such a "technology flows" table, Scherer used it to reweight the available R&D data by line of business into measures of both "origin" and "imported" (used) R&D from elsewhere, assuming that the flow of knowledge to industry i from industry j was proportional to the fraction of j's patents deemed to be "destined" for industry i. In explaining labor productivity growth at the two- and four-digit SIC level, Scherer showed that the "transmitted" user R&D variable had a higher coefficient and was often more significant than the own "origin" or process R&D variables. His results are quite sensitive, however, both to the time period chosen for the analysis and the particular subset of industries included in it. Griliches and Lichtenberg (1984) used a more detailed set of data on TFP growth at the four-digit SIC level and found less of an effect for the "used" R&D component, in part because they concentrated on manufacturing industries only, excluding some of the more important spillover "using" industries outside of manufacturing. They also interpreted the equation as measuring improvements in materials and equipment bought from other industries, with the improvements being proportional to the R&D investments of the producing industries and the size of their flows being related to the allocation of R&D effort as measured by patents destined for the using industry. Englander et al. (1988) use Canadian patent data cross-classified by industry of origin and industry of potential use to construct similar measures of own R&D and a reweighted measure of the R&D from other industries and countries. Mohnen and Lepine (1988) use the same Canadian data to analyze cost reductions in 12 Canadian industries. In both studies the results differ by industry and time period and are sensitive to the exclusion of an overall measure of disembodied technical change, such as a time trend.

Jaffe (1986, 1988) comes closest in looking for the second type of spillovers, the disembodied kind. His distance measure is one of proximity in technological research space and does not imply flows in a particular direction. His measure of "closeness" between any two firms uses the overlap in the distribution of their patents by detailed patent class and indexes it by the uncentered correlation coefficients between them, their "angular separation." The assumption is made that two firms that are active in the same technological areas, as indicated by their taking out patents in the same patent classes, are more likely to benefit from each others research results. Jaffe constructs for each firm a measure of an available "pool" of outside R&D, with the R&D of other firms being weighted inversely to their estimated technological distance from the particular firm. Jaffe "validates" this measure by including it in the estimation of a production function and patent equation for these firms, finding a positive effect of the "pool" variable. He also estimates profit and Tobin's Q equations where the pool variable shows up with a negative coefficient. More recently, Jaffe (1989) has studied the effects of geographic proximity to university based research on the patenting of closely located firms with similar research objectives. Henderson, Jaffe and Trajtenberg (1990) are currently using patent citation frequencies to university based patents to assess the contribution of universities to industrial productivity in general.

The alternative to the search for a concept of technological closeness or distance is to use the research investments of different industries as separate variables. But that is not really feasible. At best we would have about 30 years of data for each of about 20 industries. Bernstein and Nadiri (1991) "solve" the problem by choosing only a few industries each, using "correct" sign restrictions for this purpose. But the multicollinearity between the various R&D series can easily produce "wrong" signs at some point in such a procedure. The alternative of using "significance tests" is also unattractive. Statistically insignificant spillovers may still be economically quite important. More generally, it is doubtful that such a discontinuous "in-or-out" modeling is really the right way to approach this problem. We need to weight and to aggregate somehow and that is what the idea of technological distance is for: to tell us how to weight the different research series and collapse them into one or a few variables so that the empirical importance of R&D spillovers can be estimated and assessed. With such estimates it would be possible to compute not only the return to a particular R&D expenditure in its "own" industry but also the total returns to R&D including the spillovers beyond its own industry's borders.

A number of studies have used the cost function framework to estimate the effect of spillovers; see Bernstein (1989), Bernstein and Nadiri (1988, 1989 and 1991) and Mohnen and Lepine (1988). The advantage of the cost function approach is that it is often more flexible in the functional form used and that it benefits from imposing more structure, considering the impact of R&D spillovers not only on total costs but also on the amount of labor and intermediate products demanded. The disadvantage is the required use of prices and the appearance of output on the right-hand-side of the equation. One is unlikely to have good input price data which differ significantly across firms and across time, especially R&D and physical capital prices. Moreover, both prices and output should be "expected" rather than actual values. The use of ex post output produces 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.

Another way of looking for R&D externalities is to look for measures of R&D output rather than input (expenditures). Schankerman (1979) uses a weighted measure of patents granted in other industries in explaining the productivity of R&D, in terms of patents granted, in a particular industry. He gets positive results for the variable, but their significance is suspect, since the underlying data, patents granted by SIC, were constructed by the Patent Office (OTAF) on the basis of a "concordance" which had a large amount of double counting of the same patents in different industries; see Griliches (1990). Wu (1990), following Caballero and Lyons (1989), uses total factor productivity growth in other industries (with an attempt to adjust for cyclicality) as her measure of potentially available externalities. This raises the more general question of what can be learned from looking at productivity residuals across and between industries.

The hypothesis of R&D spillovers does not really require the assumption that these effects are larger in the "home" industry and that they can be measured by the fraction of the total effect spilled out, using the own effect as a base of measurement. It is quite possible for an idea to have its entire effect elsewhere than where it was originated. Nevertheless, a common approach to the measurement of spillovers assumes that they are proportional to the "first order" effects within the "sending" industry. That is, an industry that has more productivity growth has also more to spill out. This view leads one to look for correlations, contemporaneous and lagged, among TFP or production function residuals across industries. Wu, for example, using 36 manufacturing industries tries to construct "spillover" measures weighting other industry residuals by various technological and input consumption distance measures. Her results are meager and difficult to interpret both because the mean effect of technological change across all industries, including the overall spillover effect, is already absorbed in the industry constants and cannot be distilled again from the residuals, and because current cross-correlations dominate the results. But it is unlikely that real technological spillovers are contemporaneous. One would expect them to be subject to quite long lags. Statistically, the procedure is equivalent to looking for particular patterns of "spatial" residual correlations in some technological space spanned by the various industries, both across and between industries and across time. While there is a literature on both spatial correlation and on dynamic factor models, it is doubtful that we can estimate today convincing models of overlapping, shifting relations of mutual causality, given the poorness of the underlying productivity measures. Moreover, such models are in general not identifiable in the context of a free contemporaneous cross-correlation of disturbances (errors) across industries. The prior information necessary to identify them consists exactly of the same kind of information on patterns of influence and their relative lag structures discussed earlier in the context of R&D spillovers. In econometrics there is also no free lunch.

The problem of the timing of such effects has yet to be given adequate attention. The usual procedure has been to construct some measure of R&D capital for each unit and then use it in the construction of the aggregated "pool" or available "spillover" measure. But this ignores the possibility that spillovers take more time than "own" effects, both because of secrecy and the time it may take for them to be expressed in new products and processes and diffused throughout the relevant industrial structure. Given the diffuse nature of such effects and the likely presence of long and variable lags, it is not surprising that "significant" findings are rare in this area. Moreover, it makes one somewhat skeptical about positive findings already reported even though one wants very much to believe in their reality.

The expectation of significant lags in such processes is also one reason why I do not put much trust in recent studies which find effects of "aggregate" externalities, either from aggregate activity, as in Caballero and Lyons (1989), or from investments in aggregate public capital, as in Aschauer (1989) and Munnell (1990). Besides partially adjusting for errors of measurement in the other variables and proxying for left out capacity utilization effects, the more or less contemporaneous timing of such effects is just not plausible. The apparent correlations are due more to common business cycle effects, partially induced by shifts in government expenditures, than to direct externalities. Not that I do not believe in the contribution of public capital to the functioning of our economy, only I doubt that it can be measured adequately in this fashion.

The major research questions in this area remain measurement questions. How much of the R&D in an area or industry is "spillable"? Who are the potential recipients? And is there an interaction between their own research endeavors and what they get out from the potentially available pool of the results of others? The first question is related to the level of aggregation in the data. This has been explored to some extent in the agricultural economics literature, especially by Evenson (1984 and 1988). The research done within a particular state experiment station is a mixture of a variety of research programs devoted to different sub-areas and sub-products. Only a part of it is relevant to the outside world. The larger the unit and the more variegated it is, the more likely it is that there will be less there to spill out than may be indicated by the aggregate numbers. Evenson, in his work, tries a number of "deflators" which are either proportional to the size of a state or unit, to the number of different climatic regions within a state, or to a variance like measure of the internal concentration of research within fields or subfields. The issue of the relevant size unit becomes very difficult but also crucial when we abandon the safe harbor of constant returns models and set sail looking for externalities. It is clear that a small specialized computer firm is likely to benefit from some of IBM's research results, but probably much less than would be implied by the total resources devoted by IBM to computer research. The small firm will have specialized in a much narrower niche than is described by the available SIC classification.

One other way of measuring externalities of R&D remains to be mentioned. If there are significant externalities to R&D within an industry, then the computed returns should be higher at the industry than the firm level. A comparison of firm-based R&D results with those found using various industry aggregates does not, however, indicate consistently higher R&D coefficients at the aggregate level; see Mairesse and Mohnen (1990, Tables 2 and 3). There may be two reasons for this negative finding. In the R&D "intensity" version of estimated productivity equations, the coefficient of the R&D variable can be interpreted as a gross rate of return, containing also a depreciation component. The relevant private rate of depreciation of R&D stock at the firm level is potentially much higher than what is likely to prevail at the overall industry level; see Pakes and Schankerman (1984). The latter contains a large component of social returns whose depreciation or obsolescence should be much less. Hence, without taking into account explicitly the difference between private and social obsolescence rates it may prove difficult to make much of such a comparison. Moreover, for the same reason, one should probably use different R&D capital concepts at different levels of aggregation, based on rather different depreciation assumptions.

In spite of all these difficulties, there has been a significant number of reasonably well done studies all pointing in the same direction: R&D spillovers are present, their magnitude may be quite large, and social rates of return remain significantly above private rates. A selective list of such findings is presented in Table 11.1. The estimated social rates of return look surprisingly uniform in their indication of the importance of such spillovers. While one must worry whether this is not just the result of self-imposed publication filters, my own involvement in this work and my acquaintance with many of the other researchers in this area leads me to believe in the overall reality of such findings.

Can R&D spillovers account for a significant proportion of the observed growth in per capita income and measured TFP? If we take the estimates in Table 11.1 seriously, they imply an estimate of μ, the elasticity of output with respect to aggregate "outside" R&D, between about half of and double the elasticity of output with respect to private R&D. Taking the upper range of these estimates, with $\gamma = 0.1$ (see Mairesse and Sassenou (1991) for a survey of estimates), and a set of "stylized" and optimistic facts about economic

Table 11.1 **Selected Estimates of Returns to R&D and R&D Spillovers**

I. *Agriculture*[a]	*Rates of Return to Public R&D*	
Griliches (1958) Hybrid corn	35–40	
Hybrid sorghum	20	
Peterson (1967) Poultry	21–25	
Schmitz-Seckler (1970) Tomato harvester	37–46	
Griliches (1964) Aggregate	35–40	
Evenson (1968) Aggregate	41–50	
Knutson-Tweeten (1979) Aggregate	28–47	
Huffman-Evenson (1991) Crops	45–62	
Livestock	11–83	
Aggregate	43–67	
II. *Industry*	*Rates of Return to R&D*	
Case Studies		
Mansfield et al. (1977a)	25	56
I-O Weighted	Within	From Outside
Terleckyj (1974) total	28	48
private	29	78
Sveikauskas (1981)	10 to 23	50
Goto-Suzuki (1989)	26	80
R&D Weighted (patent flows)		
Griliches-Lichtenberg (1984)	46 to 69	11 to 62
Mohnen-Lepine (1988)	56	28
Proximity (technological distance)		
Jaffe (1986)		30% of within
Cost functions		
Bernstein-Nadiri (1988, 1989)		20% of within
differs by industry	9 to 27	10 to 160
Bernstein-Nadiri (1991)	14 to 28	Median: 56% of within

[a]Adapted from Huffman-Evenson (1991, Table 14.2).

growth: y (growth in output per worker) = 0.03, c (growth in capital per worker) = 0.03, k (growth in R&D capital per worker) = 0.04, l (growth in number of workers) = 0.01, s (share of capital) = 0.3, which includes the assumption of rather rapid growth in knowledge capital (due, say, to a lower social depreciation rate), yields the following values for the growth equation

$$(y - 1) = 0.3(c - 1) + 0.1(k - 1) + 0.2k + t$$

$$0.03 = 0.3 \times 0.03 + 0.1 \times 0.04 + 0.2 \times 0.05 + t$$

$$= 0.009 = 0.004 + 0.010 + 0.007\,,$$

where R&D returns can account for up to half of the growth in output per worker and about three-quarters of the measured TFP growth, most of the explanatory effect coming from the spillover component, which is large, in part, because it is the source of increasing returns (the growth in l not being subtracted from it). A decline in overall R&D growth from about 5 percent per year to 2 percent (or less), such as happened between the early 1960s and middle 1970s, could, in this interpretation, have contributed significantly to the productivity slowdown, with the R&D contribution to growth dropping from 0.014 to 0.005, and accounting for about a half or more of the slowdown; see Griliches (1988).

This "back-of-the-envelope" calculation may exaggerate the potential magnitude and effect of such spillovers, both because of the upward selectivity bias in the results reported in Table 11.1, and because of a range of measurement issues discussed at greater length in Griliches (1979 and 1995). It does indicate, however, the importance of knowing the actual magnitude of such effects. But progress here awaits the appearance of better data and the development of better econometric techniques for tracing the interaction between firms and industries over time in an ill-defined and changing multi-dimensional space of technological opportunities.

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