Measuring the Returns to R&D

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Abstract

We review the econometric literature on measuring the returns to R&D. The theoretical frameworks that have been used are outlined, followed by an extensive discussion of measurement and econometric issues that arise when estimating the models. We then provide a series of tables summarizing the major results that have been obtained and conclude with a presentation of R&D spillover returns measurement. In general, the private returns to R&D are strongly positive and somewhat higher than those for ordinary capital, while the social returns are even higher, although variable and imprecisely measured in many cases.

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1. Introduction

Returns to investments in R&D and other innovation assets are a subject of considerable interest to accountants, firm managers, policy makers, and economists in general. The reason is obvious: investment in R&D and innovation is expensive and one would like to be sure that there is a positive return, and would also like guidance as to how to direct investments in the future. Policy makers are especially interested in the social or economy-wide returns to R&D investment, which can be greater or less than the private returns to individual firms, while economists and managers are more often interested in the private returns, the former because they are interested in the incentives firms face for undertaking such investment, and the latter because they are the decision makers in question. That is, accountants and firm managers are interested in this topic because they would like to use the information to help guide their investment decisions and evaluate the success of various strategies.

For half a century, economists have been developing various methods of estimating the rate of return to research and development spending (R&D). For the most part, the literature has used the familiar growth accounting framework augmented with measures of R&D investment or capital, at various levels of aggregation from plant level all the way up to the macro-economy. This approach essentially relates the growth of total factor productivity (TFP) to R&D. To put it another way, the residual growth factor in production that is not accounted for by the usual inputs (labor, capital, intermediate inputs) is assumed to be the product of R&D that produces technical change.

R&D expenditures may differ in type but their object is always to increase the stock of knowledge in order to find new applications and innovations. A distinction is usually made between basic research, applied research, and development, according to how close the research is to commercial applications. In general the closer it is, the larger the expenditure share devoted to it. Similarly, a distinction is made between R&D directed toward invention of new methods of production (process R&D) and R&D directed towards the creation of new and improved goods (product R&D). R&D can also be broken down on the basis of its funding source, either private or public, or on the basis of whether it is carried out by businesses or by other organizations such as universities and research institutes. Finally, R&D statistics are available classified by economic sector or industry and, for the portion of R&D devoted to research, by scientific and technical fields.

R&D can increase productivity by improving the quality or reducing the average production costs of existing goods or simply by widening the spectrum of final goods or intermediate inputs available. As a consequence, we may observe profit increases, price reductions, and factor reallocations as well as firm entry and exit. Moreover, R&D carried out in one firm/sector/country may produce positive spillover effects in other firms/sectors/countries. Such spillovers are all the more likely and significant as the sender and the receiver are closely related. "Pecuniary" spillovers occur when new or improved intermediate goods or investment goods are sold to other firms at prices that reflect less than the full value of the progress they incorporate.

In contrast, "Non-pecuniary" spillovers are those that come from the knowledge created by R&D as it disseminates and becomes useful to other firms.

Before continuing, we would like to caution the reader that the "return" to R&D is not an invariant parameter, but the outcome of a complex interaction between firm strategy, competitor strategy, and a stochastic macro-economic environment, much of which is unpredictable at the time a firm chooses its R&D program. Therefore, there is no reason to expect estimates of the *ex post* returns to be particularly stable over time or across sectors or countries. And in the case of social returns, they are not even tied to some kind of cost of capital. However, these estimates can still be useful for making comparisons between various financing systems, sectors, or countries, and can also be a guide to policy-making toward R&D. Nevertheless, keep in mind that the measurement process is not a search for a "scientific constant."

1.1 Brief history of the literature

There are a number of prior surveys of the literature on the economic measurement of returns to R&D. Some have catalogued the various results and others have discussed the many analytical problems that confront a researcher in this area. The first and pioneering analytic survey was that by Griliches (1979) in the *Bell Journal of Economics,* although some of the issues discussed there were anticipated in his 1973 survey. In that article Griliches laid out the structure of the problem in the production function context and discussed two major measurement difficulties: the measurement of output when a great deal of R&D is devoted to quality improvement and nonmarket goods and the measurement of input, specifically, of the stock of R&D capital. He returned to these themes in Chapter 4 of the Kuznets lectures of 1996, published posthumously (Griliches, 2000). Also see his 1998 book, which collects all the articles he wrote on this topic.

Hall (1996) reviews what was known to that date about the private and social returns to R&D, and discusses some of the measurement problems. Hall (2007) presents a detailed analysis of the problem of estimating the depreciation of R&D capital at the firm level. Mairesse and Sassenou (1991) focus on the econometric studies dealing with firm data, while Mairesse and Mohnen (1995) expand the topic to take in econometric studies at all levels of aggregation and to include measures of R&D spillovers. The surveys by Debresson (1990), Mohnen (1990a), and Griliches (1992) deal exclusively with spillovers.

The concern with which government policy makers view the problem of measuring the returns to R&D is reflected in a large number of government publications on the topic. For example, see the U.S. Bureau of Labor Statistics (1989) and Sveikauskas (2007), as well as past issues of the OECD *STI Review*. For the UK, see the report by Griffith et al. (2003), and for Canada, Longo (1984) and Mohnen (1992a).

This chapter will concentrate on the econometric approach to measuring returns to R&D that is based on the production function and its cost or profit dual. By far the largest number of quantitative studies has been performed using this approach, which can be applied in various ways at the plant, firm, industry, or country level.

There are alternative approaches to valuing R&D econometrically, the most important of which is the market value or Tobin's q methodology, which relates the current financial value of a firm to its underlying assets, including knowledge or R&D assets. This methodology is clearly limited in use to the firm level, and to economies with thick publicly traded financial markets and we will not survey it extensively here. There are recent surveys of this literature by Hall (2000), Czarnitzki et al. (2006), and Grandi et al. (2009). For an overview of the accounting approach to the problem together with recommendations for improvements in reporting, see Lev (2001).

In the following pages we first present the general theoretical framework for the models customarily used in estimating returns to R&D, and then we discuss in some detail the complex measurement issues that arise in practice. This is followed by a review of the empirical results that have been achieved using these models that includes an extensive set of tables which organize the various results. The final substantive section of the paper discusses the measurement of R&D spillovers and presents some of the results on their impact across firm and across country. We conclude with a brief discussion of future research topics.

2. General theoretical framework

As observed earlier, much if not most of the literature that measures the returns to R&D, whether at the micro or the macro level, relies on a production function framework, where the output of a firm, a sector, or an economy is related to its stock of R&D or knowledge capital, and potentially to the stock of external R&D capital, along with other inputs. Two major approaches have been followed: the primal approach, which estimates a production function with quantities as inputs, and the dual approach, which estimates a system of factor demand equations derived from a dual (cost function) representation of technology.[1] We present each of these approaches in the next two sections of the chapter.

2.1 The primal approach

The Cobb-Douglas production function augmented with knowledge capital terms takes the following (stylized) form:

$$Y = AL^{\alpha}C^{\beta}\left[K\right]^{\lambda}\left[K^{o}\right]^{\varphi}e^{u} \qquad (1)$$

where Y is a measure of production,[2] L is a measure of labor input, C is ordinary (tangible) capital, K is own knowledge (intangible) capital, K^o is external knowledge capital and u is a disturbance. External knowledge capital can be that held by other firms in the sector, or, in the case of economy-wide estimation, that held by other countries. The coefficient γ measures the elasticity of output with respect to own R&D capital and φ the elasticity of output with respect to external R&D capital (the spillover term).

[1] There are also a couple of studies, few thus far, which have examined the R&D productivity connection using technological frontier analysis (see Fecher 1992, Fecher and Perelman (1989, 1992) and Perlman 1995). The idea is to estimate frontier (or best practice) production functions instead of average production functions, to decompose productivity growth into movements of the frontier and toward the frontier and then to regress the estimated changes in these two components on, among other things, R&D. The estimation of best practice technology can be achieved from a cost function or from a production function.

[2] This formulation has abstracted from the presence of intermediate inputs such as energy and materials. Therefore production should be measured by value added in their absence; by gross output if these inputs are available.

Ordinarily, logs are taken of this equation, converting it to a linear model that can be easily estimated. Writing the equation using *t* to denote time and *i* to denote firm or sector:

$$y_{it} = \eta_i + \lambda_t + \alpha l_{it} + \beta c_{it} + \gamma k_{it} + \varphi k^o_{it} + u_{it} \qquad (2)$$

In deriving this equation, we have implicitly assumed that the log of technical progress (*A*) can be written as the sum of a sector or firm-specific effect η_i and a time effect λ_t. Many variations of this assumption are possible, although not all will be identified, given the data available. Frequently equation (2) is converted to a growth rate version by first differencing:

$$\Delta y_{it} = \lambda_t + \alpha \Delta l_{it} + \beta \Delta c_{it} + \gamma \Delta k_{it} + \varphi \Delta k^o_{it} + \Delta u_{it} \quad (3)$$

In this case, an expression for TFP growth as a function of R&D capital stocks and a disembodied trend can be derived by subtracting the terms involving the other inputs from the left hand side of the equation. Note that the additive sector or firm effect has disappeared, and that the time effect is now a growth rate effect rather than a level (that is, it is relative to the initial observation).

By definition, the elasticity $\gamma = \rho(K/Y)$, where ρ is the marginal productivity of R&D capital. Consequently and dropping the external R&D capital term for the moment, equation (3) can be rewritten as

$$\Delta y_{it} = \lambda_t + \alpha \Delta l_{it} + \beta \Delta c_{it} + \rho \frac{(R_{it} - \delta K_{i,t-1})}{Y_{it}} + \Delta u_{it} \qquad (4)$$

where *R* is gross R&D investment, and δ is the depreciation rate of R&D capital. If we assume a constant marginal product γ and a constant discount rate *r* along with an infinite planning horizon, then ρ can be given the economic interpretation of a marginal gross (of depreciation) internal rate of return.[3] After subtraction of the R&D depreciation rate, we obtain a marginal net internal rate of return. As opposed to specification (3), specification (4) estimates the gross rate of return to R&D directly. As usually implemented, the depreciation rate is assumed to be approximately zero, so that a simple measure of R&D intensity (R&D to output ratio) can be used on the right hand side.

At the aggregate level, using gross R&D to measure the R&D intensity may not be a bad approximation, but at the firm level, it is clearly problematic, since much of their R&D investments are "replacement" investments.[4] The true net investment rate may be substantially

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[3] The internal rate of return is the one that equates a dollar of investment in R&D to the present value of the marginal productivities of that investment in the future: $1 - \int_0^\infty \rho e^{-(r+\delta)} dt$. Solving this integral yields $\rho = r+\delta$.

[4] For a derivation of the bias involved in ignoring the R&D depreciation rate, see Mairesse and Sassenou 1991, footnote 19). Goto and Suzuki (1989) report large differences depending on whether net or gross R&D intensities are being used. Hall and Mairesse (1995) find that the rates of return increase by an increment of about 5-7% when net intensities are used.

lower than that measured by the gross R&D spending-sales ratio. To see the consequences of this assumption, we use the equation for capitalized R&D presented later in the chapter to construct an approximation to net R&D investment:

$$\Delta k_{it} = \frac{R_{it} - \delta K_{i,t-1}}{K_{i,t-1}} \cong \frac{R_{it} - \delta R_{i,t-1} / (\delta_i + g_i)}{K_{i,t-1}} = \frac{R_{it}}{K_{i,t-1}} \left[1 - \frac{\delta_i}{(1+g_i)(\delta_i + g_i)} \right]$$
$$\Rightarrow \hat{\rho} \cong \left[1 - \frac{\delta_i}{(1+g_i)(\delta_i + g_i)} \right] \rho \cong \left[\frac{g_i}{\delta_i + g_i} \right] \rho \qquad (5)$$

This equation shows that the estimated gross rate of return in the R&D intensity formulation underestimates the true rate of return by the ratio of R&D growth to the sum of R&D growth plus depreciation. In a typical sample, the median growth of real R&D ranges from about 3 to 10 per cent per annum. If the depreciation rate is 15 per cent, this implies that the true gross rate of return will be 2.5 to 5 times the estimated value, a point which seems to have gone unnoticed in the literature.

Recall that ρ and γ are related simply by the ratio *K/Y,* so that in principle, estimates obtained for one can be easily translated into estimates of the other. However, in most samples the R&D intensities are very heterogeneous, so it will make quite a bit of difference whether one estimates ρ or γ directly and derives the other one. Conceptually it seems preferable to assume that the rate of return ρ is constant across units rather than the elasticity γ (which is more likely to vary directly with the share of R&D capital itself), but such estimates have proved less stable than the elasticity estimates. The explanation lies in the uncertainty of R&D output: the *ex ante* expected rate of return is what the firms consider when investing and it is likely to be roughly equal to the cost of capital (possibly with a risk adjustment and lemons' premium), but the *ex post* returns, which is what we measure, could be highly variable.

Using the production function framework, it is possible to estimate the model in another way. If we assume constant returns to scale, competitive behavior, and profit-maximizing levels of factors of production, we can replace the production elasticities with the appropriate total cost shares. For example, the elasticity with respect to labor would be equal to the labor share in total cost.[5] Equations (3) and (4) can then be replaced by the following:

$$\Delta TFP_{it} = \lambda_t + \gamma \Delta k_{it} + \Delta u_{it} \qquad (6)$$

$$\Delta TFP_{it} = \lambda_t + \rho \frac{(R_{it} - \delta K_{i,t-1})}{Y_{it}} + \Delta u_{it} \qquad (7)$$

[5] Using ideas in Hall (1998) and Griliches and Mairesse (1984), the constant returns assumption can be relaxed to an assumption of homogeneity, that is, proportionality among the production coefficients that varies with their shares. We develop this later in this section.

where $\Delta TFP_{it} = \Delta y_{it} - s_{Lit}\,\Delta l_{it} - s_{Cit}\,\Delta c_{it}$ is the Divisia index of total factor productivity growth.[6] The same kind of simplification could be applied to the equation in levels (2).

In the last two specifications, additional information is added to the model regarding producer behavior and market structure. A more general model would allow for scale economies, mark-up pricing in the presence of imperfect competition and intertemporal R&D investment decisions. Such a model is developed by Klette (1994) following on the work of Hall (1988). In the version presented here, we have added an additional variable factor, materials M_{it} that is needed for identification. Starting with equation (3), multiply the output elasticities for the variable inputs labor and materials by μ, where μ is the mark-up ratio of price to marginal revenue (or marginal cost). The output elasticity of the quasi-fixed factor (physical capital) is given by the difference between the scale elasticity σ and the sum of the other output elasticities:

$$\Delta y_{it} = \lambda_t + \mu\left[\alpha(\Delta l_{it} - \Delta c_{it}) + \theta(\Delta m_{it} - \Delta c_{it})\right] + \sigma\Delta c_{it} + \gamma\Delta k_{it} + \Delta u_{it} \qquad (8)$$

The model as it has been presented so far basically concerns process R&D, although in estimation on firm-level data with sector or economy-wide deflators, some of the benefits of product R&D will be present in the output measure in the form of higher relative prices for the output of particular firms. That is, the production function being estimated is a form of revenue production function with relative price times quantity on the left hand side. But a richer approach is to actually model the demand side. Suppose we have a log-linear expansion of the demand growth function in terms of price and quality change (proxied by R&D capital growth):

$$\Delta y_{it} = \eta\Delta p_{it} + \xi\Delta k_{tt} \qquad (9)$$

where η is the price elasticity of demand, p_{it} is the price of the firm's output relative to the sector or economy, and ξ is the elasticity of demand to a change in product quality. Defining sales as $S_{it} = p_{it}Y_{it}$, equation (9) can be rewritten as

$$\Delta y_{it} = (1+\eta)^{-1}\left(\eta\Delta s_{it} + \xi\Delta k_{tt}\right) \qquad (10)$$

If we combine equations (8) and (10) and ascribe the price markup entirely to the price elasticity of demand, i.e., $\mu = \eta(1+\eta)^{-1}$, then we obtain the following:

$$\Delta s_{it} = \tilde{\lambda}_t + \alpha(\Delta l_{it} - \Delta c_{it}) + \theta(\Delta m_{it} - \Delta c_{it}) + (\sigma/\mu)\Delta c_{it} + (\gamma/\mu - \xi/\eta)\Delta k_{it} + \Delta\tilde{u}_{it} \qquad (11)$$

The tildas on the time dummies and disturbances reflect the fact that these now contain both supply and demand influences. Equation (11) could also be estimated in a TFP growth form under the assumptions that allow the shares to be measured directly. It combines the cost-reducing and product-creating aspects of R&D, as well as allowing for imperfect competition, scale economies and markup pricing. The real output variable, which is hard to measure because of firm-specific changes in quality, has been substituted out in favor of a simple gross sales

[6] In discrete time, the Divisia index of TFP growth would be approximated by a Tornqvist index, where the weights are the arithmetic means of the cost shares over two successive periods.

variable. The R&D elasticities are now a combination of output elasticities and price elasticities, and cannot be identified separately by this equation alone, although identification might be achieved if firm-specific prices are available, as they are in some establishment censuses.

2.2 The dual approach

The dual approach relies not just on a technological representation but also on the assumption of some kind of optimizing behavior. Under the assumptions of cost minimization, profit maximization, or firm value maximization, the theorems of duality can be exploited to represent the technology by a cost function, a profit function or a value function, and to derive from them the factor demand and/or output supply equations. A distinction can be made between variable and quasi-fixed inputs, i.e., those that are optimized and those which for various reasons such as adjustment costs are not at their optimal long-run value. Equations describing the adjustment of the quasi-fixed inputs to their long-run value can also be derived, by formulating some kind of dynamic model, such as the adjustment cost model based on an intertemporal optimization. The model can moreover be enlarged to incorporate financial choices, pricing decisions, or multiple outputs. A great deal of structure is imposed on the estimation, allowing the estimation of a number of economic effects within a unified framework and increasing the efficiency of the estimation, if the assumed specification is correct. The technology is often represented by a flexible functional form, which does not assume *a priori* that the rates of return on R&D are constant, but allows them to vary in conjunction with variations in factor prices, R&D spillovers, output and quasi-fixed inputs.

To illustrate the dual approach, we present a simplified version of the model constructed by Bernstein and Nadiri (1991). The technology is represented by a variable cost function:

$$C^V = C^V(w_t, Y_t, C_{t-1}, \Delta C_t, A_t) \tag{12}$$

Where C^V is the variable cost (the sum of the costs of the variable inputs only), w_t is the n-dimensional vector of variable input prices, C_{t-1} is the m-dimensional vector of quasi-fixed input quantities, Y_t is the level of output, A_t is a shift variable reflecting technical change, and $\Delta C_t = C_t - C_{t-1}$ is the m-dimensional vector of net investment in the quasi-fixed inputs, entering because of adjustment costs.[7] The R&D stock of knowledge K is a component of the vector C. At period t, the capital stocks at the end of the preceding period (C_{t-1}) are the relevant inputs. Adjustment costs to R&D are justified by the installation costs of R&D equipment, the search costs for R&D personnel, the setup costs of R&D projects, and the fact that R&D programs generally take time and are not easily sped up.

As in the primal approach, the demand function and hence the differential role of product and process R&D can be explicitly modeled. The inverse product demand function is given by

$$p_t = D(Y_t, K_{t-1}, z_t) \tag{13}$$

[7] To simplify the presentation, the firm or sector index i is omitted.

where p_t is the output price, K_{t-1} is the R&D stock, and z_t is a vector of exogenous variables affecting demand.

The producer's input and output choices over his planning horizon (assumed to be infinity for simplicity) are determined by maximizing the expected present value of the net inflow of funds:

$$\max_{\{Y_s, V_s, C_s\}} \sum_{s=t}^{\infty} E_t \alpha^{t,s} \left[D(Y_s, K_{s-1}, z_s) Y_s - C^V(w_s, Y_s, C_{s-1}, \Delta C_s, A_t) - q_s (K_s - (I_m - \delta) K_{s-1}) \right] \quad (14)$$

where E_t is the conditional expectation operator, V is the n-dimensional vector of variable inputs, $\alpha^{t,s}$ is the discount factor, q is the row vector of quasi-fixed input prices, I_m is the m-dimensional identity matrix, and δ is the m-dimensional diagonal matrix of depreciation rates of the quasi-fixed inputs.

A flexible functional form (such as a translog, a generalized Leontieff, or a generalized McFadden) is used for the demand and variable cost functions. The input demand and output supply functions are then readily derived from them. By Shephard's lemma, the variable input demand function in competitive factor markets are given by

$$v_{is} = \left(\frac{\partial C^V}{\partial w_i} \right)_s \qquad i = 1, \ldots, n \quad s = t, \ldots, \infty \quad (15)$$

In monopolistic or imperfectly competitive markets, the output supply is given by

$$p_s^Y \left[1 + \left(\frac{\partial \log D}{\partial \log Y} \right)_s \right] = \left(\frac{\partial C^V}{\partial Y} \right)_s \qquad s = t, \ldots, \infty \quad (16)$$

This equation includes a price mark-up over marginal cost that is determined by the inverse of the price elasticity of the demand function.

The accumulation of R&D (or other capitals) is given by the following Euler equation:

$$w_{rs}^e + \left(\frac{\partial C^V}{\partial K} \right)_{s+1}^e + (1 + \rho_s) \left(\frac{\partial C^V}{\partial \Delta K} \right)_s - \left(\frac{\partial C^V}{\partial \Delta K} \right)_{s+1}^e - \left(\frac{\partial D}{\partial K} \right)_{s+1}^e Y_{s+1}^e = 0 \qquad s = t, \ldots, \infty \quad (17)$$

where $w^e_{rs} = (1+\rho_s)\, q_{rs} - (1-\delta_r)\, q^e_{r,s+1}$ is the R&D capital rental rate, $(1+\rho_s) = \alpha^{s,s+1}$, the index r denotes the R&D component of a vector and the superscript e denotes the conditional expectation of a variable. Similar Euler equations, except for the absence of the last term from the demand equation, describe the accumulation of the other quasi-fixed inputs.

The equations describing the technology (12), the inverse product demand (13), the factor demands (15), (17), and the output supply or pricing equation (16) are then estimated jointly. More restricted versions of this kind of model do not account for the demand effects of R&D (equations (13) and (16) are not estimated), or do not model the accumulation of the quasi-fixed inputs. In the latter versions, referred to as temporary equilibrium models, the quasi-fixed inputs are completely fixed, their variation does not appear as an argument in the cost function and hence the Euler equation (17) is eliminated. Alternatively all inputs can be treated as variable (static equilibrium models) and then equation (15) holds for all inputs.[8]

Ex ante, in the model of intertemporal maximization, over the planning horizon R&D earns the normal rate of return under the expectations which hold at the time of decision making. *Ex post*, those expectations might not materialize, and hence the marginal R&D investment could earn more or less than the normal rate of return. If we are interested in short-run growth accounting, we need only the short-run rate of return, earned in the period just following the investment. Whereas, in the primal approach, this rate of return is estimated by its marginal (revenue) productivity, in the dual approach it is estimated by its shadow price, normalized by the acquisition price of R&D. In the presence of a demand effect, the shadow price consists of the marginal cost and marginal revenue effects. Again, if we assume the constancy of the shadow price of R&D, the R&D depreciation rate and the discount rate, and an infinite planning horizon, the shadow price of R&D less its depreciation rate can be interpreted as a net rate of return.

As can be seen from equation (17), if we were in the long run without growth, that is, when $K_t = K_{t-1}$, adjustment costs would disappear in the model as formulated above, and the shadow price of R&D would equal the normal rate of return plus the depreciation rate less the inflation rate, in other words the net (of depreciation) normal real rate of return.[9] In the short run, however, which corresponds to the observed data, the shadow price at period t matches the long-run rate plus the difference in the marginal adjustment costs between two adjacent periods. The short-term rate of return can thus fall above or below the normal rate of return.

The differences of specification in the studies using the dual approach are even more numerous than in the primal approach. First, the choice of how to represent the technology (by a total cost, variable cost, profit, or value function) implies an a priori assumption about which inputs are variable and which ones are quasi-fixed and about which inputs and output decisions are considered endogenous or exogenous in the model. Second, the choice between a temporary equilibrium and a dynamic model implies a choice between adding or not equations describing the evolution of the quasi-fixed inputs. Third, an indicator of autonomous technological progress (time dummies or a time trend) is generally not included given its collinearity with the stock and output variables, and this may imply some misspecification. Finally, the choice of functional form takes us back to the choice between a constant rate of return and a constant elasticity of R&D. A translog function will estimate elasticities, while a quadratic functional form estimates marginal productivities as a function of levels of the explanatory variables. In addition, any flexible functional forms, the quadratic being a major exception, are not amenable to aggregation and make the fitting of micro models to macro data problematic.

Having presented the basic framework for estimating the returns to R&D, in the next section we turn to some measurement issues.

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[8] Even more general models would allow for monopsonistic input markets, strategic competition with R&D reaction functions, or induced technical change.

[9] If the adjustment costs had been formulated in terms of gross investment, the long-run rate of return would be the normal discount rate augmented by an expression involving the marginal adjustment costs associated with replacement investment.

3. Measurement Issues

In this section, we discuss a certain number of technical and conceptual problems that arise in the econometric studies of R&D and productivity. Some of them pertain to productivity analysis in general, others are specific to R&D. After a brief presentation of the issues, we summarize what has been learned regarding their important and relevance, confining ourselves to those issues which are particular to R&D. Most of the work exploring these problems of sensitivity to measurements and specifications and of various sources of bias in the estimation has been done using the primal approach. To organize our presentation, we distinguish three categories: the measurement of productivity, the measurement of the R&D stock of knowledge, and the issues of exogeneity and heterogeneity.

3.1 Measurement of productivity

Productivity can broadly be defined as the ratio of an output index to an input index. Hence the first issue is how to properly measure output and input and how to separate out the R&D effect from other determinants or explanations of productivity.

3.1.1 Measurement of output

Output can be measured by gross output, value-added, or sales. Value-added is the output obtained from the combined use of labor and capital, and can be defined as gross output less purchased inputs such as materials. Thus gross output is the value of the combined use of these two primary inputs plus the intermediate inputs. Frequently sales, which is gross output less increases in inventories of finished goods, is used as a proxy for output. Theoretically, gross output is to be preferred over value-added as a measure, because it allows for substitution between materials and the other two inputs. However, there are reasons to prefer the use of value-added, especially when using firm data. First, the materials-output ratio can vary a great deal across firms because of different degrees of vertical integration; second, proper modeling of the demand for intermediate inputs would probably require modeling adjustment costs related to the stocking of materials; third, good data on materials and value-added are often not available when using data based on public firm accounts instead of the census data available within national statistical agencies.

The studies by Cunéo and Mairesse (1984) and Mairesse and Hall (1994) on French data show that the estimates of R&D elasticities derived from a value-added specification do not differ by much from those obtained using sales without including materials. As exposited in Griliches and Mairesse (1984), omitting materials in the sales regression yields an upward bias in the R&D elasticity, because materials are correlated with R&D. In the cross section dimension, where the proportionality of materials to output is likely to hold, the bias in the R&D elasticity is predictable, being roughly equal to the estimated R&D elasticity times the materials share in output. However, in the within dimension, materials may be sluggish in responding to output changes, and hence the bias is less easy to quantify. These predictions are confirmed in the previously mentioned studies by Mairesse and co-authors.

A more substantial problem, particularly acute in relation to R&D, is the incorporation of quality changes in price deflators. New or improved products make their way into the price indices only with a substantial lag, if at all. The consequence is that R&D-intensive goods, as outputs or as inputs, are underestimated and that their prices are overestimated. For a striking illustration of the difference the use of hedonic prices can make to the estimated rates of returns to R&D, see Griliches (1994a). Regressing TFP growth rates on R&D intensities across industries, he obtains an estimated rate of return to R&D of 35.7% for the 1973-89 period. When the computer industry, which is the only that has quality changes incorporated in its output price index, is excluded from the regression, the rate of return drops to 13.4%. But when TFP growth in semiconductors and pharmaceuticals is also corrected for quality change in outputs, and TFP growth in the computer industry is corrected for quality change in the inputs of semiconductors, the estimates rise again to 34.8%, even without including the computer industry. Hanel (1994), using Canadian industry data, and Mairesse and Hall (1994), using U.S. firm data, also report an outlier effect in the computer industry.

With panel data, quality differences can be captured by sector-time dummies, even in the absence of good prices, leaving only the inter-firm differences. The R&D estimates are thus biased but only to the extent that sector prices or dummies do not fully capture the quality differences and the latter are correlated with the explanatory variables. Note that if one is interested in the private returns to R&D, this potential bias is not a problem, as those returns can come either through increased productivity, or through increased prices or markups relative to competitors, and it would be incorrect to omit the latter effects. See the earlier discussion of incorporating the demand equation into the model for way of identifying these effects separately.

3.1.2 Measurement of the inputs

Three issues regarding the correct way to measure the inputs in productivity analysis are particularly relevant for R&D: the R&D double-counting and expensing bias in the estimated returns to R&D, the sensitivity of these estimates to corrections for quality differences in labor and capital, and the sensitivity with respect to variations in capital utilization. We discuss each of these in turn.

First, since R&D expenditures are composed of labor, capital, and material costs, they are likely to be counted twice, unless the conventional inputs are cleared of their R&D components. Moreover, when output is measured by value-added, value-added should include net R&D on the output side, because often value-added does not include R&D when the latter is expensed. Schankerman (1981) shows that double-counting of R&D results in mismeasured input quantities and cost shares. The bias due to expensing can go either way depending on the evolution of R&D intensity.

Cunéo and Mairesse (1984) found a substantial downward bias in the R&D elasticity when the inputs were not corrected for R&D double-counting and expensing. The bias was mostly prevalent in the cross-section dimension and not in the time or within-firm dimension. In Hall and Mairesse (1995), Harhoff (1994), and Mairesse and Hall (1994), the bias appears in both dimensions. When the rate of return is estimated from levels in the variables, the excess rate of return interpretation, although empirically plausible, is theoretically questionable. Schankerman (1981) shows that it is not necessarily correct, even using a simple Cobb-Douglas functional form; what matters is the correlation between the measurement errors and R&D. Cunéo and Mairesse (1984) argue that the excess rate of return interpretation is theoretically correct with a linear production function, but that empirically it depends on what varies and what remains relatively constant over the sample. Interpretation as an excess rate of return is more likely when the bias appears in the cross-section but not in the within firm dimension.

Ideally, when aggregating the various inputs, individual productivity differences should be allowed for by adopting a weighting scheme such as the Divisia index to construct TFP. Mairesse and Cunéo (1985), Mairesse and Sassenou (1989), and Crépon and Mairesse (1993) obtain lower R&D elasticities when different kinds of labor, corresponding to different levels of educational qualifications are introduced separately into the production function. Their elasticities for French manufacturing firms in the cross-sectional dimension decline by one half when labor qualifications are accounted for. This result is due to the positive correlation between highly qualified labor and R&D, indicating a complementarity between the two. This phenomenon does not show up in the within dimension as differences in the quality of the inputs do not change much over time. In a similar way to labor, differences in the quality of the physical capital stock have been modeled by adding a capital age variable to the regression. However, Mairesse and Sassenou (1989) and Crépon and Mairesse (1993) find little different in the estimates of R&D coefficients when this is done.

Finally, whereas first differencing controls for permanent differences across firms, it leaves too much cyclical noise and measurement error in the data. In the within firm dimension, the rates of return to R&D are therefore difficult to estimate. Long-differencing (i.e., over 5 to 10 years) helps in removing the cyclical variation. Hall and Mairesse (1995) report more significant R&D elasticities (but not rates of return) using long-differenced rather than first-differenced data. The cyclical effect (although not the measurement error) can also be captured by a variable measuring the rate of capacity utilization, as in Mohnen (1992a). Some studies using the dual approach (e.g., Mohnen et al. 1986 and Bernstein and Nadiri 1991) have modeled adjustment costs to explain the sluggishness of input adjustments to cost changes.

3.1.3 The form of the technology

When assessing the role of R&D in productivity growth, one has to keep in mind that other factors affect the level and the growth rate of TFP, among which are the returns to scale and technical change that is not a direct result of R&D. If not accounted for, these other determinants of productivity could bias the estimates of the returns to R&D.

In the studies based on the production function, returns to scale tend to be constant in the cross section dimension (across firms). Controlling for permanent firm effects (that is, within firm), the elasticities and rates of returns to R&D tend to be higher when constant returns to scale is imposed or when factor elasticities are replaced by observed factor shares (see Griliches and Mairesse 1984, Cunéo and Mairesse 1984, Griliches 1986, Griliches and Mairesse 1990, and Hall and Mairesse 1995). Consistent with this result, the decreasing returns to scale tend to reduce the conventional input elasticities as well (especially that for capital). Griliches and Mairesse (1984) explain this result by the fact that the sources of downward bias such as measurement error are stronger in the within dimension, where much of the relevant information has been removed. Griliches and Hausman (1986) provide a useful analysis of the effects of measurement error on panel data estimates in general, with an application to the production function.

In the cross-sectional study of productivity, account should be taken of firm-specific variations in management skills, sector-specific appropriability or technological opportunity conditions. In panel data, these factors will be captured by dummy variables, either at the industry or the firm level. There are also variations across the time dimension that may have little to do with the real R&D-productivity relationship, such as macro-economic conditions, errors in deflators that are common to a sector or the economy, or other economy-wide measurement errors. Thus it is invariably a good idea to include time dummies when doing the analysis at the plant, firm, or sector level. At the macro-economic level, this option is not available, which renders the analysis effectively impossible due to the confounding effects of other changes on the relationship between R&D and productivity.[10]

3.2 Measurement of knowledge capital

The underlying assumption behind the econometric measurement of the returns to R&D is that R&D creates a firm-level stock of knowledge that yields returns into the future. Constructing such a stock from a string of R&D investments requires depreciating the past stock in some way. How fast do R&D expenditures enter and exit the relevant stock of knowledge? What is the starting point? How should we convert nominal flows into real terms? We now turn to these issues.

Almost all the studies reviewed here have used a simple perpetual inventory or declining balance methodology with a single depreciation rate to construct the knowledge capital produced by R&D investments:

$$K_{it} = (1-\delta)K_{i,t-1} + R_{it} \qquad (18)$$

where K is the knowledge stock of firm i at time t, R denotes real R&D investment at time t and δ is a suitably chosen (private) depreciation rate.[11] A few authors (Hall and Hayashi 1989, Klette 1994) have suggested a simple variation of this model that incorporates the idea that the productivity of R&D depends on the level of the current stock:

$$\log K_{it} = \sigma \log K_{i,t-1} + (1-\sigma)\log R_{it} \qquad (19)$$

In this multiplicative formulation, the R&D impact on next period's knowledge stock depends on the level of last period's stock. Exploring the impact of alternative specifications of this kind may be a useful avenue for future work. See Bitzer and Stephan (2007) for another alternative.

However, the workhorse of R&D stock estimation remains the perpetual inventory model, leaving us with the problem of choosing a depreciation rate. From the perspective of a firm, this is the rate at which the private returns to past R&D investments decline if no further R&D is undertaken. Determining this rate is difficult if not impossible, for at least two reasons. First, the appropriate depreciation rate is endogenous to the firm's own behavior and that of its

[10] Obviously, including a full set of time dummies in a single time series relationship leaves nothing else to identify the impact of R&D. Some researchers have tried to avoid this problem in the past by including only a time trend or a quadratic in time, but this is a fairly unsatisfactory solution.

[11] For future reference, note also that under the assumption of constant depreciation and constant R&D growth at the firm level, equation (18) implies that the "true" R&D capital K^* (K computed using correct economic depreciation) is given by the equation $K^*_{it} = K_{it}\dfrac{\delta_i + g_i}{\delta^0_i + g_i}$, where δ_i^0 is the depreciation rate used to construct the measured K (usually 15 per cent).

competitors, in addition to depending to some extent on the progress of public research and science. Therefore there is no reason to assume that it is constant over time or across firms, although it will usually (but not always) change slowly in the time dimension. Second, identifying the depreciation rate independently from the return to R&D requires determination of the lag structure of R&D in generating returns. But years of experience with the specification of production functions, market value equations, or even patent production functions (Hall, Griliches, and Hausman 1986) has shown convincingly that this is extremely difficult, because of the lack of appropriate natural experiments. That is, in practice R&D does not vary much over time within firm, so that trying to identify more than one coefficient of R&D is problematic and leads to very unstable results. In the data used in Hall (2007), which is a fairly heterogeneous time series-cross section of firms, the variance of R&D growth rates within firms is only about 4 per cent of the variance of the levels. In addition, as has been observed by earlier authors (e.g., Hall and Mairesse 2005), the log R&D series exhibits close to random walk behavior.[12] The implication of these properties is that including more than one linear function of the (log) R&D series in an equation will be a futile exercise.

In spite of these difficulties, some researchers have attempted to estimate the private (firm-level) depreciation rate for R&D directly. One approach is to estimate the rate of obsolescence using patent renewal data; obviously this is not ideal, since the knowledge may remain useful even if patent protection is not required and since this method covers only certain kinds of knowledge, that which can be patented. Bosworth (1978) estimates the rate of obsolescence to lie in the 10% to 15% range and to be variable across cohorts, whereas Pakes and Schankerman (1984) obtain a point estimate of 25%. Klette (1994) estimates a 20% physical R&D depreciation rate using the model in equation (19) in combination with a revenue growth equation. Bernstein and Mamuneas (2006) estimate industry-specific rates that range from 18% for chemicals to 29% for electrical products. Hall (2005) uses a Tobin’s q market value equation together with data on a large panel of U. S. manufacturing firms over the 1974-2003 period. She obtains an overall estimate of 27%, with estimates ranging from 15% for pharmaceuticals to 36% for electrical product firms.

An alternative approach to estimating the magnitude of knowledge depreciation is to experiment with different rates in constructing the knowledge stock. Griliches and Mairesse (1984), Mairesse and Cunéo (1985), Bernstein (1988), Bernstein and Nadiri (1989), Hall and Mairesse (1995), and Harhoff (1994) report small differences, if any, in the estimated R&D effects when the rate varies from about 8% to 25%. Because of this evidence, most researchers use the 15 per cent that Griliches had settled on in his early work.

It is easy to see why the resulting elasticity is not sensitive to the choice of depreciation rate: assume that R&D grows over a sufficiently long period at a constant (firm-specific) rate g_i and that knowledge capital K depreciates at a firm-specific rate δ_i. Then one can show that

$$K_{it} \cong \frac{R_{it}}{\delta_i + g_i} \text{ or } \log K_{it} \cong \log R_{it} - \log(\delta_i + g_i) \quad (20)$$

[12] A typical correlogram for the first three lags of the log R&D series in the US data is (0.99, 0.97. 0.96) and the partial correlogram is (0.99, 0.00, 0.00).

As long as the growth rate and depreciation do not change very much within firm over time, they will be incorporated into the firm effect, and the estimated elasticity of output with respect to either K or R will be the same, and that for K will not depend on the choice of depreciation rate. Note that the fact that we also observe little sensitivity to the choice of depreciation rate in the cross section dimension suggests that depreciation and growth rates are not very variable across firms when compared to the level of R&D spending, or that they are not very correlated with the R&D level.

However, although the elasticity of output with respect to R&D may not be affected by the choice of the depreciation rate, the same is not true of the rate of return derived from the elasticity. To see this, note that the gross and net rates of return to K are:

$$\rho^G \equiv \frac{\partial Y}{\partial K} = \gamma \frac{Y}{K^*} \quad \text{and} \quad \rho = \gamma \frac{Y}{K^*} - \delta \tag{21}$$

where Y is output or value added, K^* is the true knowledge stock, and ρ^G and ρ are the gross and net rates of return respectively. Therefore the production function approach to measuring returns requires knowledge of δ both to compute the correct level of K and also to convert gross returns to net returns.

3.2.1 Lag effects

The use of a particular rate of R&D depreciation in the construction of the R&D stock by the perpetual inventory method presumes a certain distribution of the R&D effects over time. However, it is unlikely that the latest addition to the R&D stock becomes productive immediately, because of the lag from expenditure to innovation, and from innovation to commercialization. It seems reasonable to expect even longer lags for spillovers because of the additional diffusion lag and also for basic R&D because of the longer invention to innovation lag. Often only contemporaneous stocks are used in estimation, because of the shortness of the available time-series of R&D expenditures.

A few examples exist in the literature where the use of alternative lag distributions has been explored. Mansfield et al. (1971) report a median lag from R&D to innovation of about three years for firms. Leonard (1971) reports that "the effect of R&D upon growth on the average begins in the second year after the R&D investment and continues with steadily rising influence for at least nine years after the initial input year." Ravenscraft and Scherer (1982) cite survey responses from companies stating that 45% reported a typical time lag between the beginning of development and the first introduction of a new product of one to two years, 40% reported a lag between two and five years and 5% a lag of more than 5 years.

Using patent renewal data, Pakes and Schankerman (1984) derive a gestation lag between R&D outlay and its first revenues in the range of 1.2 to 2.5 years. From their econometric analysis, Ravenscraft and Scherer (1982) conclude that the lag structure is roughly bell-shaped, with a mean lag from 4 to 6 years. Seldon (1987) discriminates among different lags in the forest products industry on the basis of correct signs and t-statistics. The best-fitting lags were found at two years, for both private and public R&D. Adams (1990) obtains best fitting lags of 20 years for the effect of own R&D on productivity growth and of 10 to 30 years for the effects of spillovers from basic research and science. Using a similar procedure to Adams, Ducharme and Mohnen (1996) generally find lags of 5 to 6 years for own R&D and of 7 to 11 years for spillovers. Griliches and Mairesse (1984) obtain some evidence that the lag effect drops sharply after two years, but that the lag structure hardly matters for estimates obtained across firms. Hanel (1994) also obtains more significant results with lagged R&D up to a certain lag. Geroski (1989) finds that innovations continue exerting an effect on productivity growth three years after their introduction.

3.2.2 Benchmark stock and R&D deflator

The perpetual inventory method used to construct an R&D stock of knowledge from past R&D expenditures needs to have an initial benchmark stock. Generally the latter is measured by dividing the first observation of R&D expenditure by the sum of the R&D depreciation rate and an estimate of the R&D growth rate as in equation (20). Various methods are used to estimate the growth rate: the *ex post* R&D growth rate, the output or capital stock growth rate, or merely a notional value such as 3 or 5 per cent. Griliches and Mairesse (1984) and Mairesse and Hall (1995) find somewhat higher R&D elasticities within firm but not across firms when they use stocks constructed from longer R&D series.

The ideal for constructing a deflator for R&D expenditures would be a Divisia index of the prices of the various components of R&D, as done for example by Bernstein for Statistics Canada (1986). However, in practice the choice of R&D deflator does not seem to matter greatly. The U.S. Bureau of Labor Statistics (1989) study reports little difference between the use of the Jaffe-Griliches R&D deflator, which is constructed as an index of the hourly compensation index and implicit output deflator for non-financial corporations, and the GDP deflator. The Jaffe-Griliches index itself was found to approximate fairly well the Mansfield, Romeo, and Switzer (1981) Laspeyres index of price components of R&D. Harhoff (1998) reports very small differences when using sector-specific investment deflators vs. R&D deflators for Germany.

3.3 Econometric issues

3.3.1 Definition of the sample

One problem facing the econometrician is the definition of the sample from which to infer his estimates, i.e., the issues of selection bias, cleaning the data for outliers and incorrect numbers and accounting for heterogeneity.

Is there selection bias if only R&D-performing firms are included in the sample? The studies by Mairesse and Cunéo (1985), Mairesse and Sassenou (1989), and Crépon and Mairesse (1993), which in various ways impute a stock of knowledge for non-R&D-performing firms tend to show that the rate of return on R&D is not fundamentally different for the firms with and without R&D. R&D-performing firms have a higher stock of knowledge or benefit from more spillovers than those without apparent R&D activities; still the estimated stock of knowledge for non-R&D firms can be quite sizeable. However, Klette (1994) reports that non-R&D performing firms have a lower productivity performance.

Given the presence of extreme outliers with firm data, it is customary to clean the sample by removing the observations for which some variables are abnormally high or low.[13] The estimates

[13] For an example of the criteria used to clean the dataset, see Hall and Mairesse (1995).

can be very sensitive to the removal of outliers as the following two examples illustrate. Lichtenberg and Siegel (1989) report 3.8% lower rates of return on total R&D when influential outliers are discarded and 29.5% lower when a robust estimator is used instead of least squares.

Severe jumps in firm data are often the results of mergers and acquisitions. As Griliches and Mairesse (1984) illustrate, excluding the firms that merged during the sample period sharply drops the estimated R&D elasticity in the within firm dimension, but not in the across firm (total) dimension. Merger firms have higher R&D growth rates and apparently more R&D. A similar phenomenon is reported by Hall and Mairesse (1994), using a much larger sample.

As mentioned earlier, the estimates can also differ according to the R&D-intensiveness of the firms, industries, countries, and time periods. Many studies obtain higher R&D elasticities for the scientific (R&D-intensive) firms, at least in the cross section dimension (see Griliches 1980, Griliches and Mairesse 1984, Cunéo and Mairesse 1984, Mairesse and Cunéo 1985, Sassenou 1988, Odagiri 1983, Englander et al. 1988, Bartelsman 1990b, Hall 1993 and Ortega-Argilés et al. 2009). If R&D is earning an approximately normal rate of return, this result, that the R&D elasticity varies with the R&D share, is to be expected. However, in the time-series dimension, where the R&D elasticities tend to decline or even become insignificant, the difference between the two types of firms tends to shrink (Griliches and Mairesse 1984). An analogous result is found by Verspagen (1995) with industry data: in the within dimension he only obtains significant R&D elasticities for the high-tech industries. But recall that within estimates are likely to have more downward bias from measurement error, and in both these cases, much of the variation in R&D intensity is removed when firm or industry effects are controlled for. Finally, using aggregate data, Soete and Verspagen (1992) and Coe and Helpman (1992) find that the productivity of R&D is higher in the more developed countries.

The estimated rates of return to R&D can also vary a great deal between sectors. Link (1981) estimates rates of return for large firms that range from 25% in chemicals to 160% in transportation equipment. Spreads of that order of magnitude in the rates of return are reported by Bernstein (1988, 1989), Bernstein and Nadiri (1988, 1989, 1991), and Mohnen and Lépine (1991) using industry data. The variation is even more pronounced for the estimated social rates of return. The reasons for these variations are likely to be quite different from those for elasticity differences. As discussed earlier, we would expect *ex ante* rates of return to be equalized across sectors, but there can be wide variations in *ex post* measures due to the great uncertainty of success that accompanies R&D.

3.3.2 Disaggregation of R&D

Most studies find a higher rate of return for process as compared to product R&D (Clark and Griliches 1984, Griliches and Lichtenberg 1984a, Link 1982, Terleckyj 1982, Scherer 1982, 1983, Hanel 1994). Why should product R&D have lower return? First, the impacts of the two types of R&D are difficult to disentangle and to a certain extent they are complementary. Second, the effects of product R&D are difficult to measure because of the poor reflection of quality improvements in the price indices. Third, new products imply adjustment costs that lower productivity in the short run: as Clark and Griliches (1984) put it "new products involve a start-up and debugging phase of varying length in which new equipment and new tasks are specified and learnt."

Regarding the sources of R&D funding, a lower rate of return (or a less significant one) is reported by many authors to public rather than private R&D, both at the private and social level (Bartelsman 1990a, Griliches 1980, 1986, Griliches and Lichtenberg 1984b, Hanel 1988, Leonard 1971, Levy and Terleckyj 1989, Lichtenberg and Siegel 1991, Mansfield 1980, Nadiri and Mamuneas 1994, Patel and Soete 1988, Park 1995, Soete and Verspagen 1992, Terleckyj 1974, Hanel 1994). Lichtenberg (1993) and Poole and Bernard (1992) even report instance of negative contributions of government R&D.

Although it is likely that private firms are less efficient in their research when using the public purse, there are other reasons that explain this lower return for public R&D. First, the studies are generally restricted to the manufacturing industries, where a good deal of government R&D is directed to the service sectors, where a large share of the externalities thus created can only be measured imprecisely if at all, because of measurement difficulties of the output in the service sector in addition to quality problems (Griliches 1994). Second, a large share of public funds is spent precisely in areas where the risk is higher or where the government is already active because there is a public goods problem (such as the areas of defense and health). Third, public R&D can encourage private R&D and hence have an indirect rate of return (see David and Hall 2000 for a review of this evidence, which is mixed). Fourth, as Leonard (1971) reports, in the U.S., there is empirical support for the hypothesis that federal funds are concentrated in a few industries, such as aircraft and communications, where the returns are lower because of the magnitude of the R&D – that is, there is indeed overinvestment. Note that government R&D can yield high returns in basic research (see Link 1981 for US evidence), or in firms with high R&D budgets and a sizable government share of the market (see Cunéo 1984 and Hall and Mairesse 1995 for France).

A higher return is also generally reported on basic R&D as opposed to applied or development R&D (Lichtenberg and Siegel 1989, Lichtenberg 1992, Link 1981, Griliches 1986, Mansfield 1980). As Mansfield's (1980) results suggest, basic R&D is really long-term R&D. So the higher reward for basic R&D could simply reflect a higher risk factor associated with long-term R&D commitments. Again, the interaction effect or complementarity of different types of R&D may be important. For example, Link and Rees (1990) estimate higher rates of return to R&D for firms involved in university research, this effect being higher for smaller than for larger firms.

3.3.3 Simultaneity

Another potential source of bias in the estimate of the elasticity or rate of return to R&D from a production function is the simultaneity in the choices of output and inputs (see Griliches and Mairesse 1984 for a formal derivation of the bias expression). In the absence of data on factor prices (as is typically the case with firm data), a semi-reduced form can be estimated, where labor, materials, and output are expressed as functions of the fixed factors capital and R&D. If the left-out factor price variables are uncorrelated with the capital variables, it is then possibly to obtain unbiased estimates at least of the ratio of the capital and R&D elasticities. This assumption is more likely to be true in the within than in the total or cross section dimension. Griliches and Mairesse 1984 obtain higher R&D-capital elasticity ratios with the reduced form estimates, especially within firm. In contrast, Hall and Mairesse (1995) report lower R&D elasticities with the reduced form specification in both the total and the long differenced dimension, and hardly any differences in the within dimension.

Another way of handling the simultaneity issue is to use instrumental variable or Generalized Method of Moments (GMM) techniques, exploiting the orthogonality between instruments (e.g., appropriately lagged explanatory variables) and the error term. This approach has been followed by a number of researchers (among others, Hall and Mairesse 1995, Klette 1992, Bond et al. 2005, Griffith et al. 2006). Experience suggests that GMM estimates based on differences alone can be very imprecise, whereas GMM using both level equations and difference equations yields more precise estimates that are often close to those obtained by OLS (Blundell and Bond 2000).

The dual approach goes further in this direction by estimating a set of reduced form factor demand equations as functions of factor prices (more readily available at the aggregate or industry level), quasi-fixed inputs, and output (if the optimizing framework is one of cost minimization and not profit maximization). But even the dual approach can be affected by a simultaneity bias, to the extent that aggregate factor prices are correlated with aggregate input levels and that output is itself endogenous. Little systematic work has been done to verify the importance and the likelihood of these types of bias.

A simultaneity bias can also explain why some studies (e.g., Griliches and Mairesse 1984, Mairesse and Hall 1994) find higher R&D elasticities with end-of-period than with beginning-of-period R&D stocks (especially in the within firm dimension), because of the feedback from sales to current levels of investment. See also Hall et al. 1999 for some evidence on causality between output, profits, R&D, and investment.

4. Empirical estimates of the private returns to R&D

Measuring the private returns to R&D is a subject that has received a great deal of attention since early work of Griliches, Mansfield, and others. A number of approaches to the problem have been advanced and the increasingly widespread availability of large panel datasets of firms has led to a corresponding increase in the use of various econometric methods for estimating returns. In parallel with these developments, the econometrics of panel data has made enormous progress, so that we now have a wide range of techniques to address the problems of simultaneity and unobservables that are inherent in such data. In this section of the paper we give an overview of the literature and discuss some of the results that have been obtained using these methods and data.

Table 1, which is in four parts (firm production functions, industry production functions, country production functions, and cost or profit functions) gives an idea of the literature that has been created since the 1960s. Clearly, there is too much here to survey in detail. We have made a selection based on a number of criteria such as publication in easily accessible journals, the use of more developed methodologies, and our own familiarity with the work in question. In what follows we present a series of tables that summarize the results for this selection of papers. However, we encourage the reader who is interested in a particular question, methodology, or geographical area to go back to the original papers, as our summary does not do justice to the full richness of many of them, and there are differences that we have not been able to catalogue, owing to lack of space. Among these are the details of the data construction, variation in the control variables included, and variations in methods of estimation.

In the tables, we have classified the empirical studies with which we are familiar according to four criteria:

1. Whether the model is in the primal or dual form (Tables 2, 3 vs. 4).
2. Whether the data are at the firm, establishment, industry, or aggregate (country) level (all Tables, although some methods are better suited to particular levels of aggregation).
3. Whether the estimates are cross-sectional or temporal, or both (Table 2 only, the other tables are temporal only).
4. Whether or not spillovers are accounted for (Table 5 as opposed to Tables 2-4).

In each of the subsequent Tables (2 through 5), we show the author(s) and dates of the studies, the country or countries covered, the number of cross-sectional observations, and the time period. Table 2 shows results for firm and industry-level data estimated using the primal or production function approach with the log of R&D capital stock included, in two parts: 2a for cross-sectional and pooled results and 2b for temporal or within results. Here we show the estimated R&D elasticities and the rate of return to R&D, where it can be derived. We also give a brief indication of the model used (sales or value added as the dependent variable, the presence or not of industry dummies, and occasionally the method of estimation if it is not OLS). In a few cases, we indicate that the variables have been corrected for the double counting of R&D inputs.

Table 3 presents the estimated rates of return that are based on the R&D intensity version of the production function regression and Table 4 those from various versions of the dual approach. All of the models in these tables are essentially estimated in the temporal dimension. In the case of Table 3, the regression is a growth rate regression; in Table 4, the identification typically comes from the temporal variation of the data. We often give a range of estimates in both Tables 3 and 4, which correspond to the range estimated across the individual industries or countries.

4.1 R&D elasticity and rate of return: estimates based on the production function

Table 2 shows the estimates of research elasticity and rate of return obtained using firm data and based on specifications of the (Cobb-Douglas) production function with R&D capital. The two panels 2a and 2b show estimates based on the cross-sectional dimension and those exploiting the temporal dimension of the data respectively. Overall, the results are plausible, with figures for research elasticity ranging from 0.01 to 0.25 but centered on 0.08 or so. In general, the cross-sectional estimates are higher than the within estimates, which are often not even statistically significant.

Cross-sectional estimates use the information on individual differences in the levels of the variables, whereas temporal estimates rest on the individual differences in the evolution of the variables, independently of their levels. That is, cross-sectional estimates are based on the levels of the variables for a given year or on individual means over a certain number of years (“between” estimates). Temporal estimates are based on the growth rates of the variables, or on the deviations from the individual means (”within” estimates). Total estimates are pooled across the cross-sectional and temporal dimension, but because the cross-sectional variation is much larger than the temporal variation within firm or industry, they tend to be close to the between estimates.

It should also be pointed out that, with a few exceptions, the cross-section estimates tend to be somewhat lower when sectoral dummies are included in the specification. The interpretation is ambiguous. On the one hand, the indicators may correct the estimates for the bias resulting from the erroneous omission of structural variables correlated to the sectoral characteristics. On the other hand, the dummies themselves may be a source of distortion to the extent that they reflect in part the return to research resulting from technological opportunities that differ by sector. The latter are probably essential for explaining the greater tendency to carry out R&D in certain sectors.

The fact that the estimates are lower and more fragile in the temporal dimension can be explained in a number of ways. A simple but important reason relates to the collinearity between the physical capital and research capital variables and the time effects reflecting autonomous technical change. Another reason is the previously mentioned one that measurement errors have a much more serious impact on growth rates than on the levels of variables (Griliches and Hausman 1986). A further factor is no doubt the omission of cyclical variables in the production function, such as person hours rather than simply employment, capacity utilization, and, more generally, the difficulties of providing a satisfactory specification of the lags and the dynamic evolution of the variables. A few of the more recent papers, such as Klette 1994, Coe and Helpman 1995, Kao et al. 1999, Los and Verspagen 2000, and Guellec and van Pottelsberghe 2001, take some steps in the direction of proper time series modeling in the panel data context.

The rate of return estimates in Table 2 are mostly based on multiplying the estimated elasticity by the average output-R&D capital ratio in the sample and are generally quite high because of the skew distribution of this variable. Table 3 presents the estimates obtained directly using the R&D intensity formulation of the model (equation (4) or (7) with depreciation set to zero). As we noted, in principle, the choice between estimating an elasticity or a rate of return hinges on which one of the two is more likely to be constant. Griliches and Lichtenberg (1984b) obtain significant coefficients only with the constant rate of return assumption. Hall (1993) reports that the latter formulation proved to be very unstable across minor sample changes and was also sensitive to outliers. But Crépon and Mairesse (1993) show great heterogeneity in R&D elasticities when the translog functional form is used. In fact, the elasticities tend to increase with R&D intensity, suggesting that the constant rate of return is perhaps not unreasonable. It is interesting to compare the estimates of the R&D elasticity with those of the rates of return, at least for those studies where the sample characteristics necessary to make the conversion are available. As can be seen from Table 3, the estimates of the rates of return are consistent with those derived from the research elasticity. As the results in Hall and Mairesse (1995) show, the estimated rates of return are closer to the elasticities estimated within firm or industry, as we would expect, given that both of them are temporal estimates.

On the whole, although the studies are not fully comparable, it may be concluded that R&D rates of return in developed economies during the past half century have been strongly positive and may be as high as 75% or so, although they are more likely to be in the 20% to 30% range. Looking at these studies, we also confirm two findings made earlier about the R&D elasticity: the estimated returns tend to decrease and become less significant when sector indicators are introduced and when the returns to scale are not constrained to be constant. We find that estimates based on industry data are generally quite close to those obtained from firm data. Finally, studies based on plant or establishment data produce results similar to those obtained with firm data, not surprisingly, since they are invariably forced to use firm level R&D data due lack of disaggregated data on R&D. Given the presence of “within firm” spillovers, it is not even clear that disaggregation would be useful. The only exception is Clark and Griliches (1984), who have line of business data on R&D and even they report rates of return similar to the lower ones obtained at the firm level.

4.2 R&D rate of return: estimates based on the cost or profit function

Turning to the results obtained using the dual approach, we note first that because they rely mostly on variation in factor prices for identification, they are for the most part conducted at the industry level or higher. In addition, they are sometimes estimated with separate coefficients for each industry and/or country; in that case we observe a range of estimates in Table 4. Because of major differences in specification, comparing the results of the various studies is sometimes difficult. For example, the rates of return are constrained to be the same across industries in Bernstein (1988) and Bernstein and Nadiri (1989), in the former because R&D is being treated as a variable rather than a quasi-fixed factor and in the latter because the estimated rates are long-term rates of return (ignoring adjustment costs).

Looking at the estimates, we note that most of them are quite reasonable, on the order of 10% to 20%, although Bernstein (1989) and Mohnen and Lépine (1991) obtain a range across industries that is somewhat higher using a translog cost function applied to Canadian data. In general, the rates of return to R&D exceed those for physical capital in these papers. Bernstein (1989), who estimates the two types of rates in a comparable manner, finds the rates of return to R&D in Canada to be 2.5 to 4 times greater than those to physical capital.

In principle, one of the advantages of the dual approach as it has been implemented is that it allows measurement of the adjustment costs for R&D capital (as well as those for physical capital). For example, Bernstein and Mohnen (1998) find that R&D stock adjustment in the U.S. is relatively slow, with 5% taking place in the first year, whereas for Japan 41% takes place in the first year. Mohnen (1992) notes that these estimates can vary quite a bit and are often insignificantly different from zero. In his comparison of OECD countries, the amount of R&D gap closed in the first year ranged from zero in France to 30% in Japan.

5. R&D Spillovers and the social returns to R&D

The R&D executed in one firm can affect the productivity performance of other firms operating in the same industry or in other industries, either locally or abroad. A discovery in one firm, sector or country can trigger new avenues of research, inspire new research projects or find new applications in other firms, sectors or countries. For example, the synthetic fiber initially developed in the chemical industry and subsequently applied in the textile industry. Or the well-known examples of laser technology, which has found applications in many areas, and the invention of the microprocessor, upon which an entire industry has been built.[14]

Conceptually it is useful to distinguish two kinds of spillovers: rent spillovers and knowledge spillovers (Griliches, 1992). The first type occurs when a firm or consumer purchases R&D-incorporated goods or services at prices that do not reflect their user value, because of imperfect price discrimination due to asymmetric information and transaction costs, imperfect

[14] For more examples in the history ot technical change, see the series of books by N. Rosenberg, in particular Rosenberg (1976, 1982a, 1982b).

appropriability and imitation, or mismeasurement of the true value of the transaction due to the lack of hedonic prices. The more competitive are markets, the less ability firms have to appropriate the benefits of their R&D and the more pecuniary spillovers will take place. By contrast, the more prices are corrected for quality improvements, the less we should observe spurious R&D spillovers.

The second type of spillover occurs when an R&D project produces knowledge that can be useful to another firm in doing its own research. Knowledge is a rival and only partially excludable good. Because of weak or incomplete patent protection, inability to keep innovations secret, reverse engineering and imitation, some of the knowledge and benefits from R&D are not kept within the firm. The more knowledge is codified and the higher is the absorptive capacity of other firms, the more knowledge spillover will take place. The concept of knowledge spillovers is very relevant for growth and development, because it lays the foundation for further knowledge creation and diffusion. It is important here to distinguish between spillovers and technology transfer. Technology transfer refers to trade in technology, which occurs when an agent sells a piece of technology with a price attached to the transaction. A non-pecuniary spillover, on the contrary, refers to an unintended transfer of knowledge, in which no payment is involved.

It is important to note that the topic of social returns to R&D is closely intertwined with that of R&D spillovers. From the perspective of a firm, spillovers can come from R&D done 1) by other firms in the sector, 2) by firms in other industries, 3) by public research laboratories and universities, and even 4) by firms, laboratories, and governments in other countries. From the perspective of the economy, the first three are components of the social or aggregate return, whereas the fourth is again an (unpriced) spillover. So whether we label something a spillover depends on whether it is being created by the unit under investigation or by an entity external to that unit.

How large are the social rates of return on R&D that result from the sum of private rates and the within economy spillovers? This question has been investigated in two fashions. The first one is based on case studies and relates to specific R&D projects. Due attention is paid to the various costs and benefits, private and social, present and future, associated with a particular innovation or R&D project, some of which may require the econometric estimation of the consumer and the producer surpluses derived from R&D. The second one is the econometric approach, which estimates a general relationship between productivity and R&D, irrespective of the particular environment that is being analyzed.

In this section of the chapter, we first discuss a few illustrative case studies, and then we present some aggregate productivity-R&D results. This is followed by a more detailed examination of the literature that traces spillovers via connections between firms, industries, and countries. Before proceeding, we note that one of the important questions about R&D spillovers is the extent to which they are localized to an urban area, region, or even country. The work we discuss here has little to say on this topic, and we refer the reader to Feldman and Kogler in this volume, as well as to the recent survey by Autant-Bernard, Mairesse, and Massard (2007).[15]

5.1 Case studies

A prime example of the case study approach is the pathbreaking paper by Griliches (1958) on the calculation of the social rate of return to research in hybrid corn. He adds up all private and public R&D expenditures on hybrid corn between 1910 and 1955, cumulated to 1955 using an external interest rate of 10%, and compares them to the net social returns over that period, cumulated to 1955, plus the projected future returns, where the net returns are assumed to be equal to the value of the increase in corn production with a price change adjustment. He arrives at a perpetual annuity of returns of 7$ per dollar spent on R&D, or to an equivalent internal rate of return equalizing R&D expenditures and net social returns of 35% to 40%.

Much work on the social returns to R&D has been done on agriculture in the form of detailed case studies and estimations of producer and consumer benefits (see Ruttan (1980), Griliches (1992), and Huffman and Evenson (1993) for a list of references to such studies). Most conclude to underinvestment in agricultural research with social rates of return as high as 100%. In the same vein Seldon (1987) computes internal rates of return for R&D in the US Forest Product Industry that are even higher than those reported for agricultural research.

Mansfield et al. (1977) compute the private and social internal rates of return of 17 industrial innovations. Private benefits are measured by the profits to the innovator, net of the costs of producing, marketing and carrying out the innovation, and net of the profits the innovator would have earned on products displaced by the innovation, with an adjustment for the unsuccessful R&D. Social benefits are obtained by adding to the private benefits the change in consumer surplus arising from the possible price reduction and profits made by the imitators and by subtracting the R&D costs towards the same innovation incurred by other firms as well as possible environmental costs. The results indicate that the social rate of return generally exceeds the private rate by a substantial margin: the median social rate of return is about 56% against a median private rate of return of about 25%. Along the same lines, Tewksbury et al. (1980) examine the rates of return on 20 innovations. They obtain a median social rate of return of 99% against a median private rate of 27%.

Bresnahan (1986) evaluates the welfare gain from the reduction in the price-performance ratio of computers used in the financial services (banking, insurance, brokerage and related business). As no real output is available for these services, he assumes that the sector acts as an agent for its consumers. The value of the computer price-reducing innovation in this sector is inferred from the willingness to pay by the firm and its downstream customers. He estimates that between 1958 and 1972 the spillover from the adoption of mainframe computers in the financial services sector of the U.S. was at least five times the size of the expenditure for it in 1972.

[15] For surveys on R&D spillovers in general, see Griliches (1992, 1995), Nadiri (1993) and Mohnen (1990, 1996); on international R&D spillovers in particular, see Mohnen (1998), Branstetter (1998), Cincera and van Pottelsberghe de la Potterie (2001).

In the area of medical research, Weisbrod (1971) applies a cost-benefit framework to estimate the internal rate of return to poliomyelitis research. Comparing the basic research and vaccination costs to the benefits of saving mortality, morbidity and treatment costs, he estimates a return of about 12%. Trajtenberg (1989) estimates the welfare effect of computed tomography (CT) scanners from a multivariate accounting for hedonic prices. Comparing them to the R&D expenditures in CT scanners he comes up with a capitalized benefit/cost ratio of 270%.

Bach et al (1992) do not provide figures but describe the various ways in which the European Space Agency (ESA) program was beneficial to society on the basis of interviews with ESA contractors: the emergence of new products, new technologies, improved product characteristics, new organizational modes, the creation of networks, the training of scientists, managers and personnel.

The case studies described above illustrate how valuable this approach can be, given the long and variable lags between R&D and the full social returns, which render empirical estimation very difficult. However, such case studies tend to focus on "winners," innovations that have been successful, and may therefore undercount the full cost of excavating the dry holes which was also necessary before these innovations took place. That is, given uncertainty of outcomes, not all research projects will lead to success, and those that do will need to earn a high rate of return to cover the ones that fail. So there is a role for aggregate analysis, even though it can be difficult to tease out the effects of R&D from other factors.

5.2 Productivity growth accounting at the aggregate level

In principle, the econometric approach to estimating the aggregate or social returns to R&D offers a simpler and more comprehensive way of measuring these returns. It usually involves the inclusion of an aggregate economy-wide R&D stock in the usual TFP growth equation. Unfortunately, a single TFP time series can be driven by other factors that are correlated with R&D as well as R&D itself, and it is difficult to adequately control for them. The best one can do is the kind of growth accounting exercise now being performed by national statistical agencies, which simply impose a cost of capital on R&D and are therefore able to construct its share (e.g., see Corrado, Hulten, and Sichel 2005, 2009 and Hulten (this volume)).

A few of the studies in Table 5 contain regressions of this form, but the majority go further by specifying the channel through which the spillovers come and estimating a return to this external R&D. We defer the discussion of the results in the table until after we present the methods used to measure the spillovers.

5.3 Measuring spillovers

Most of the results in Table 5 have been obtained by adding a measure of external R&D to the standard production or cost function framework used in the earlier tables. The R&D spillover variable is measured as a weighted sum of the R&D stocks from sources outside of the firm:

$$S_{it} = \sum_{j \neq i} a_{ji} R_{jt} \qquad (22)$$

where the a_{jt} weights are proportional to some flows or proximity measures between firm, industry, or country *i*, the receiver of R&D spillover, and firm, industry, or country *j*, the source of R&D spillover. Various flow related weights have been used in the literature: intermediate input transactions (Terleckyj, 1980), investments in capital goods (Sveikauskas, 1981), hiring of R&D personnel, attendance at workshops, seminars or trade fairs, collaborations, adoption of new technologies, flows of patents (Scherer, 1984) or innovations (Sterlacchini, 1989) from industry of origin to industry of use, and patent citations. The intuition is that the more *j* trades with *i*, invests in *i*, collaborates with *i* or gets cited by *i*, the more it is likely to diffuse its knowledge to *i*. Spillovers can also be measured independently of any economic transaction simply on the basis of proximities in various types of space. These proximities can be uncentered correlation coefficients between positions in patent classes (Jaffe, 1986), fields of research (Adams and Jaffe, 1996), qualifications of personnel (Adams, 1990) or lines of business.

Measures of proximity that are independent of any economic transactions are expected to capture pure knowledge spillovers. Rent spillovers, in contrast, are likely to occur whenever monetary transactions take place, i.e. with trade, direct investment, technology payments, hiring of workers, research collaborations, and mergers and acquisitions. In practice the two types of spillover are hard to dissociate, because, on the one hand, knowledge flows are often concomitant with user-producer transactions and the capture of rents, and on the other hand, knowledge gains can be used to reap economic rents.

Taking the primal approach as an example, this measured R&D spillover term is then introduced into an extended Cobb-Douglas production function besides the stock on own R&D:

$$Q_{it} = f(X_{it}, R_{it}, S_{it}, T_{it}, \varepsilon_{it}) \qquad (23)$$

where Q_{it} is output, X_{it} are the conventional inputs, R_{it} denotes the own stock of Research and Development (R&D), a proxy for the stock of knowledge, T_{it} is an index of technological change and ε_{it} is a random error term. The return from outside R&D is then estimated as the marginal effect of S_{it}, which represents an elasticity or a marginal productivity depending on the chosen functional form of the production function.

A couple or remarks are worth making at this point. First, while rent or knowledge spillovers are expected to be positive, there can also be negative spillovers associated with R&D. Bloom et al. (2007) find evidence for a market stealing effect for spillovers in the industry segment space as opposed to the technology space. This is the case at the firm level when new products render old products obsolete (creative destruction) and at the social level when R&D is used as a mere strategy to preempt competition or when patent races lead to duplicative R&D (what Jones and Williams (1998) call congestion externalities). Second, while it is reasonable to assume that knowledge gets transmitted more easily the closer are the issuer and the receiver, it may be argued that there is more knowledge to gain if the cognitive distance between them is larger (Nooteboom et al. 2007). Third, whereas most studies have aggregated the diverse sources of R&D knowledge into some kind of index, some authors have followed the vectorization approach, i.e. included all individual sources of outside R&D as separate arguments in a production function (Bernstein and Nadiri 1988). While this approach does not choose *a priori* a certain ad hoc weighting scheme, it suffers from multicollinearity and consequent difficulty of identifying the individual contributions of spillover sources.

Fourth, the rate of return on R&D can also be estimated from a dual representation of technology, e.g. a variable cost function, where it appears as a quasi-fixed input (Bernstein 1988, 1996, 1998, Bernstein and Nadiri 1988, 1989, Nadiri and Prucha 1990, Mohnen and Lépine 1991, Mohnen 1992a, Nadiri and Mamuneas, 1994, Bernstein and Mohnen 1995, Nadiri and Kim 1996b, Bernstein and Yan 1996, 1997, and Rouvinen, 2002). As discussed earlier, these models can describe a static equilibrium where all factors of production, in particular R&D, are at their optimal level, or they can model a partial equilibrium where some factors are quasi-fixed and describe a dynamic adjustment process to the long-run equilibrium via the modeling of adjustment costs. They models are generally based on a flexible functional form for the dual representation of technology that allows through the estimation of derived factor demand equations and cross-equation parameter restrictions to estimate separate rates of return for each industry and a possible factor bias of own R&D and R&D spillovers. Fifth, the R&D spillovers are usually expressed in terms of productivity increases, but they could also be captured in terms of patents (Jaffe 1986, 1989), market values (Jaffe 1986), or innovation counts (Acs et al. 1992).

Spillovers have been estimated at various levels of aggregation - countries, sectors, firms, projects – and combinations thereof – intra-sectoral and inter-sectoral, domestic and international. In general they have been found to be quite large, but rather imprecisely estimated. In addition, many of the estimates are obtained using models without time trends or time effects, so that the external R&D coefficients may be biased upward due to the presence of confounding influences and the general increase in the R&D share in developed country economies during the time periods covered.

The social rate of return is obtained by adding the private rate of return (the benefit to the firm that performs the R&D) to the sum of the returns on outside R&D for all recipients of spillovers from that firm:

$$\frac{\partial Q_{it}}{\partial R_{i,t}} + \sum_{j \neq i} \alpha_{ij} \frac{\partial Q_{jt}}{\partial S_{jt}} \tag{24}$$

The magnitude of the social rate of return depends of course on the number of spillover receivers. For example the social rate of return of U.S. R&D will be greater if all countries of the world are included as potential U.S. R&D spillover recipients than if only the G-7 countries are involved. E.g., compare the estimates of Coe and Helpman 1995 for spillovers from the G-7 with those of Coe, Helpman, and Hoffmaister 1997 for spillovers from 22 developed countries.

Which weighting matrix is more appropriate and to the extent that the weighting reflects the channels of transmission of R&D spillover, which channel is the most important? Van Meijl's (1997) results clearly show that the estimated social rates of return may vary a great deal depending on the weighting matrix used. Kaiser (2002) tests various ways of aggregating outside knowledge into a spillover construct on the assumption that horizontal (intra-industry) spillovers should be associated with high scores for horizontal sources of knowledge indicated by firms in innovation surveys (i.e. from competitors) and the vertical (inter-industry) spillovers are associated with vertical sources of knowledge (i.e. from customers and suppliers). Intra-industry spillovers are hard to measure. Uncentered correlations of firms' characteristics or skill mix predict inter-industry spillovers better than the Euclidian distance between firm characteristics, geographical distance between firms, or a measure of imitation hazard (from perceived obstacles of innovation revealed in innovation surveys). In a special issue of *Economic Systems Research* (vol. 9(1), 1997) a number of authors have tried to compare the performance (in significance and economic returns) of different types of spillovers (on the basis of patent flows, patent citations, intermediate inputs and capital goods transactions). The ideal aggregator differs by sector and the identification of spillover channels from the simultaneous use of different spillover measures quickly runs into collinearity problems.

Crespi et al. (2008) also use the direct measures of knowledge flows, as they are revealed in the innovation surveys, for explaining TFP growth in the UK. They find that flows from competitors, suppliers and plants that belong to the same group explain half of TFP growth. Information from competitors is considered to be pure knowledge spillovers; this is correlated with the presence of multinational enterprises.

Using an endogenous growth model, Jones and Williams (1998) argue that the social rate of return of R&D should include, besides the output expansion effect examined so far, the intertemporal spillover effects, namely the increase in knowledge that will lead to more knowledge in the future and the capital gain effect that allows a decrease of the knowledge investment in favor of more consumption in the future. Along a balanced growth path they evaluate the social rate of return to exceed the static marginal productivity of R&D by a factor of 2 to 4. In a later paper, Jones and Williams (2000) build an endogenous growth model that incorporates four market distortions related to R&D investment: the appropriability problem, the presence of knowledge spillovers, creative destruction, and the externalities from R&D duplication. They use this model to show that unless the duplication externality is extremely high together with a high interest rate, a decentralized economy will underinvest in R&D, again implying higher social returns than private.

5.3.1 Empirical evidence on industry-level spillovers

Table 5 presents the results from a selection of models that have been estimated at the firm, industry, or country level. A wide range of spillover measures are used, which makes it difficult to compare the estimates, although with a few exceptions the elasticities with respect to external R&D are similar, around 0.05 to 0.09. As we alluded to earlier, one difficulty is that unlike the private returns case there is no "cost of capital" that provides a focal point for these returns. In addition, many of the dual estimates are obtained without time effects, and to some extent this may bias the external R&D coefficient upwards. In general, the rates of return obtained using the dual approach are somewhat higher than the others.

As we saw, estimates of the own rate of return based on industry data are quite close to those obtained from firm data. In contrast, the estimated rates of return to outside R&D vary considerably across studies: from 80% in Goto-Suzuki (1989) to statistically negligible in one version of Wolff and Nadiri (1993). As shown by the detailed results in Griliches and Lichtenberg (1984a), the rate of return to outside R&D seems to be highly variable, depending on the period, and in general estimates of it are less precise than those for the own rate of return. In most cases, however, the estimates are significant and indicate the existence of major spillovers of research from one industry to another. In Table 5, we can see that when the estimates are obtained separately for each industry, they range from close to zero to a full 100% (or even larger in a few cases).

As noted previously, the spillover estimate vary much more across studies than the own rate of return estimates. There are a number of reasons for this. First, the spillover effect gets larger the more receiving sectors are include in the computation of the social rate of return to R&D. Second, there is no a priori reason to expect the estimates obtained with various measure of proximity to yield similar results, since the proximities are measured in different spaces. The results might even depend on the date of the chosen weighting matrix, if the proximity between sectors evolves over time. Third, spillovers are expected to reduce variable cost, since it is reasonable to assume that firms would not adopt new ideas that are variable cost increasing. However, for strategic and absorptive reasons, firms may also feel obliged to enter the R&D race and incur the research costs that go with it. On the demand side, R&D spillovers can increase or decrease the price that a producer can charge for his product, depending on whether the new product based partly on outside R&D is substitutable or complementary to the firm's own product (Bernstein and Nadiri 1991). Adams (1990) also advances the argument that adjustment costs in knowledge absorption might cause perverse sign effects on the spillover variable in the short run. For all these reasons, spillovers can in principle be negative.[16] A final explanation for large variations in spillover return is of course the fact that nothing in the system constrains them to take on any particular value, precisely because they are unpriced and to a great extent, an accidental side effect of firm R&D strategy, even if some conscious management of disclosure does occasionally take place.

5.3.2 Empirical evidence on international spillovers

International R&D spillovers are transmitted through the same channels as those documented in the literature on technology transfer: international trade in final goods, intermediate inputs, capital goods, b) foreign direct investment (FDI), especially if it comes with manpower training to operate the new machines and to assimilate new production and management techniques, c) migration of scientists, engineers, educated people in general, or their attendance at workshops, seminars, trade fairs and the like, d) publications in technical journals and scientific papers, referencing other publications, invention revelations through patenting, patent citations, e) international research collaborations or international mergers and acquisitions, f) foreign technology payments, i.e. royalties on copyrights and trademarks, licensing fees, the purchase of patents, the payments for consulting services and the financing of R&D conducted abroad.

A highly cited study of the impact of international R&D spillovers on TFP was conducted by Coe and Helpman (1995). In this study, conducted for 22 developed countries, they used the share of imports from the sending country as weights to aggregate the R&D, confining the possible set of sending countries to the G-7 economies (Canada, France, Germany, Italy, Japan, the UK, and the US). They were able to estimate the own rate of return to R&D as 123% for the G-7, and 85% for the other 15 countries, and the spillover return from the G-7 as 32%, implying that roughly a quarter of the benefits from R&D in G-7 countries accrues to their trading partners.

Their study has been critiqued and revisited in many subsequent studies. Keller (1998) cast doubt on the trade-related interpretation of Coe and Helpman's R&D spillover by showing that

[16] For some examples of negative spillover estimates in the literature, see Jaffe (1986), Englander et al. (1988), Fecher (1992), Griliches and Mairesse (1984), Hanel (1994), and Yamada et al. (1991).

significant foreign R&D spillovers can be obtained when the weights in the construction of the spillover are random rather than based on import shares. This result suggests that the important identifying variation was in the total amount of external R&D rather than being mediated by trade. Lichtenberg and van Pottelsberghe (1998) critique Coe and Helpman's weighting of the foreign R&D stocks by means of the proportion of total imports originating from the foreign R&D sources for being too sensitive to the aggregation of the data and propose instead to normalize the imports from the recipient country by the GDP of the sending country. van Pottelsberghe and Lichtenberg (2001) provide evidence for outward FDI as another channel of international R&D spillovers. Kao, Chiang and Chen (1999) find cointegration between the TFP and R&D variables, using cointegration tests that are appropriate for panel data. When they reestimate the Coe and Helpman specification with a dynamic ordinary least squares (DOLS) estimator (which is not biased in small samples, unlike the ordinary estimator) they no longer obtain a significant effect for the trade-related foreign R&D spillover, although the domestic R&D impact is essentially unchanged.

Abdelmoula (2009) adds spatial correlations (via a spatial lag model or a spatial error model) to the Coe and Helpman specification. In the presence of other spatial effects, the foreign R&D spillover remains significant whether the weights in the spatial correlation are proportional to imports or to the inverse of the geographical distance between the countries.

The relative importance of domestic and foreign R&D contributions to total factor productivity growth depends on the channels of transmission used to estimate foreign R&D spillovers, but all channels combined it is likely that small R&D spenders have relatively more to gain from foreign R&D than big R&D spenders by the sheer size of the absorbable knowledge. It depends of course on the absorption capacity of the receiver and her openness to transmission channels, and therefore the output elasticity to foreign R&D may be higher or lower than the output elasticity of domestic R&D (as shown by van Pottelsberghe and Lichtenberg, 2001).

5.3.3 Studies of channels of transmission of R&D spillovers

At the micro level, the knowledge management literature has given rise to a new series of studies that looks in more detail at the ways in which knowledge is transmitted from firm to firm and from public research to firm, both within and across borders. A complete survey of this literature would take us well beyond the scope of this survey, but we provide a few references and comments in this section.

The first is the literature on R&D spillovers that treats the individual researcher as a carrier of tacit knowledge. There are two approaches: either researcher mobility across firms or countries brings with it the transmission of knowledge, or alternatively, researchers do not move, but their personal connections help knowledge to diffuse across borders. Almeida and Kogut (1999) discuss this phenomenon and provide an empirical example. For other examples of this literature, see Moen 2005, Kerr 2008, and Maliranta, Mohnen, and Rouvinen 2010.

A particular source of knowledge spillover that has received a fair amount of attention is the impact of academic research. Adams (1990) measures for each industry a stock of academic science by the count of past and present academic publications by science field weighted by the share of industrial scientists per field of science as well as a knowledge spillover measure by weighting the other industries knowledge stocks by the closeness of industries in the employment in science fields. For 18 U.S. manufacturing industries he estimates that academic scientific knowledge in the own industry accounts for 50% of total factor productivity growth and academic knowledge in other industries account for 25% of TFP growth, with lags of scientific publications on TFP of 20 years and 30 years respectively. Jaffe (1989) presents evidence that university research in a state produces spillovers in terms of corporate patents granted in that state: the direct elasticity is approximately 0.1 and rises to 0.6 when the inducement effect of corporate R&D is taken into account. Acs et al (1992) estimate an effect at least twice as high when the innovation output is measured by innovation counts rather than by patents granted.

One of the drivers of the empirical literature on knowledge flows has been the widespread availability of data on patent citations and scientific paper citations. For more on research in this area, we refer the reader to the chapters by Nagaoka et al. and Foray and Lissoni in this volume.

6. Conclusions

This chapter has surveyed a very large literature from the past 50 years of economic research, almost all of which has been directed to answering a few simple questions: What is the private rate of return to investing in research and development? What is the social rate of return? Are there spillovers? The questions may be simple but the answers turn out to be complex. First, it has become very clear during the course of this research that the stochastic nature of R&D outcomes means that there is nothing like a single private "rate of return" that is close to a cost of R&D capital. Second, the need for a measure of R&D depreciation or obsolescence in order to compute the net or even gross rate of return has become increasingly obvious, even though such a measure is not necessary if we simply want to measure the production R&D elasticity. Finally, we have seen that a number of fairly complex econometric methods to deal with omitted variables, measurement errors, adjustment costs, etc. have been developed in response to perceived problems in the earlier round of estimates.

In spite of the revealed complexity of the problem, we have learned something about the rates of return to R&D. They are positive in many countries, and usually higher than those to ordinary capital. The adjustment costs are also greater than that to ordinary capital. The depreciation rates appear to vary across industrial sector, probably reflecting the nature of competition and the ease of appropriability. When the production function is estimated in first-differenced form, there is a very substantial downward bias to the R&D coefficient that can be mitigated by imposing constant returns or performing GMM-SYS estimation.

As to social returns, these are almost always estimated to be substantially greater than the private returns, and often to be quite asymmetric among trading partners and industries. In addition, most estimates for public government-funded R&D suggest that it is less privately productive than private R&D, as it should be, given the fact that it targets goals that either do not show up in conventional GDP or have substantial positive externalities.

Where should this research go now? One thing we would like to know more about is the impact of increased R&D in mid-level developing countries and how this interacts with R&D spillovers to these countries. Given the general internationalization of R&D activities, it might be useful to develop the channels of knowledge transmission literature and revisit some of the international spillover estimates to see if they are changing.

Looking at the samples in the tables, one can see that almost all of the results have been obtained for the manufacturing sector, which is an increasingly small share of the economy in most developed countries. So the challenge here is to apply the methods that have been developed for that sector to data from the service and financial sectors, where there is now quite a bit of R&D and innovation. This would require some attention to the problem of under and non-reported R&D in these sectors and some rethink on what the production function actually should be.

On the data and econometrics side, much of the industry work has been done using quite aggregate sectors, partly because of R&D data availability limitations. As more of this data has become available worldwide, it may be possibly to produce more informative disaggregated industry samples. A second open set of question has to do with repeating the R&D analysis using newly available data for some countries via the Community Innovation Survey (Mairesse and Mohnen, this volume) on total innovation expenditures rather than just R&D. Clearly this would require a somewhat new conceptual framework given the varied nature of these expenditures.

Finally, because of the difficulties uncovered in constructing an R&D capital and choosing the appropriate depreciation and because the additive model is not really a very good description of knowledge production, further work on the best way to model the R&D input would be extremely desirable.

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Table 1
A Guide through the Empirical Literature

A. Production function

Cross-section or pooled	*Temporal*	*Both*
Firm or plant data		
	Mansfield (1965)	Minasian (1969)
		Bardy (1974)
Schankerman (1981)	Mansfield (1980)	Griliches (1980)
	Link (1981)	Ravenscraft and Scherer (1982)
	Link (1983)*	Clark and Griliches (1984)
	Odagiri (1983)	Cuneo (1984)
Longo (1984)	Clark and Griliches (1984)	Cuneo and Mairesse (1984)
	Jaffe (1986)*	Griliches and Mairesse (1984)
	Odagiri and Iwata (1986)	Mairesse and Cuneo (1984)
Levin and Reiss (1988)*	Jaffe (1988)*	Griliches (1986)
Mairesse and Sassenou (1989)*	Lichtenberg and Siegel (1989)	Sassenou (1988)*
	Fecher (1989)*	
	Griliches and Mairesse (1990)	
	Link and Rees (1990)	Klette (1991)
Jaian and Raut (1991)		Lambert (1991)
	Klette (1992)*	Hall (1993)
Crepon and Mairesse (1993)	Antonelli (1993)*	Crott and Mairesse (1993)
Adams and Jaffe (1994)*	Klette (1994)*	Raut (1993)*
		Hall and Mairesse (1995)
		Mairesse and Hall (1996)
		Bartelsman et al. (1996)
Crepon, Duguet, Mairesse (1998)	Capron and Cincera (1998)	Harhoff (1998)
Medda, Piga, Siegel (2003)		Los and Verspagen (2000)
Wang and Tsai (2003)	Wakelin (2001)	Harhoff (2000)*
Mairesse, Mohnen, Kremp (2005)		Griffith, Harrison, van Reenen (2004)
Ortega-Argiles et al. (2009)	Dorazelski and Jaumandreu (2008)	Bond, Harhoff, van Reenen (2005)
Hall, Foray, Mairesse (2009)		Rogers (2009)

* estimates include spillover impacts.

Table 1 (continued)
A Guide through the Empirical Literature

A. Production function

Cross-section or pooled	*Temporal*	*Both*
Industry data		
	Raines (1968)*	
	Leonard (1971)	
	Globerman (1972)	
	Griliches (1973)	
	Terleckyj (1974)*	
Link (1978)	Majer (1978)	
	Goldberg (1979)	
	Mansfield (1980)*	
	Griliches (1980b)	
	Terleckyj (1980)*	
	Sveikauskas (1981)*	
	Scherer (1982)*	
	Postner and Wesa (1983)*	Griliches and Mairesse (1983)
	Scherer (1983)	
	Griliches and Lichtenberg (1984a)*	Griliches and Lichtenberg (1984b)
	Scherer (1984)*	
	Odagiri (1985)*	
	Seldon (1987)*	
	Englander, Evenson, Hanazaki (1988)*	
	Hanel (1988)*	
	Mansfield (1988)	
	Levy and Terleckyj (1989)*	
	Fecher and Perelman (1989)	
	Geroski (1989)	
	Goto and Suzuki (1989)*	
	Sterlacchini (1989)*	
	Adams (1990)*	
	Bartelsman (1990)	
Yamada, Yamada, Liu (1991)*	Ducharme and Mohnen (1991)*	
	Vuori (1991)	
	Fecher (1992)*	
	Fecher and Perelman (1992)	
	Martin and Jaumandreu (1992)	
	Poole and Bernard (1992)	
	Perelman (1993)	
	Wolff and Nadiri (1993)*	
	Griliches (1994)	
	Hanel (1994)*	
	van Meijl (1997)*	Verspagen (1995)
	Sveikauskas (2000)	
	Griffith, Redding, van Reenen (2004)	

* estimates include spillover impacts.

Table 1 (continued)
A Guide through the Empirical Literature

A. Production function

Cross-section or pooled	*Temporal*	*Both*
Regional or country data		
Griliches (1964)		
	Nadiri (1980a)	
	Nadiri (1980b)	
	Soete and Patel (1985)	
Jaffe (1989)*	Patel and Soete (1988)	
Acs, Audretsch, Feldman (1990)*	Mohnen (1990)	
	O'Sullivan and Roeger (1991)*	
	Nadiri and Prucha (1992)	Lichtenberg (1992)
	Capron (1992)	
Joly (1993)	Guellec (1993)	
	Soete and Verspagen (1993)*	
	Coe and Helpman (1993)*	
	Park (1995)*	
	Nadiri and Kim (1996b)*	
	Coe, Helpman, Hoffmaister (1997)*	
	Keller (1997)*	
	Verspagen (1997)	
	Kao et al. (1999)*	
	van Pottelsberghe and Lichtenberg (2001)	

* estimates include spillover impacts.

Table 1 (continued)
A Guide through the Empirical Literature

B. Cost or profit function

Cross-section or pooled	*Temporal*	*Temporal*
Firm data	**Industry**	**Region or country**
		Cardani and Mohnen (1984)
Bernstein (1988) *	Bernstein and Nadiri (1988)*	Mohnen and Nadiri (1985)
	Bernstein and Nadiri (1989)*	Mohnen, Nadiri, Prucha (1986)
	Bernstein (1989)*	
Bernstein and Nadiri (1990)	Nadiri and Prucha (1990b)	Mohnen (1990)*
Suzuki (1991)	Bernstein and Nadiri (1991)*	
	Mohnen and Lepine (1991)*	Mohnen (1992b)*
	Mohnen, Jacques, Gallant (1993)	Mohnen and Gallant (1992)*
	Nadiri and Mamuneas (1994)*	Nadiri and Kim (1996a)
	Bernstein and Yan (1997)*	Nadiri and Kim (1996b)*
	Bernstein and Mohnen (1998)*	
	Bernstein (1998)	

* estimates include spillover impacts.

Table 2a
R&D elasticities of output and rates of return to R&D
Pooled estimates on firm or industry-level data using the primal approach

Study	*Sample*	*Period*	*Type of estimation*	*R&D elasticity*	*R&D rate of return*
Firm data					
Griliches (1980)	US 883 firms	1963	VA prod function with sector dummies	0.07 (0.01)	
Schankerman (1981)	US 110 firms	1963	Prod function	0.16	
Griliches-Mairesse (1984)	U.S. 133 firms	1966-77	Prod function	0.05	35% *
Cuneo-Mairesse (1984)	France 182 firms	1974-79	VA prod function; corr. for double counting	0.20 (0.01)	~90% *
Mairesse-Cuneo (1985)	France 390 chem, elec, mech firms	1974-79	VA prod function	0.18 (0.02)	~128% **
Griliches (1986)	US 386 firms	1967, 72, 77	VA prod function with sector dummies	0.09 to 0.17	51% to 76% *
Hall (1993)	US ~1200 firms	1964-90	Prod function	0.024 to 0.040	18% to 43% *
Hall-Mairesse (1995)	France 197 firms	1980-87	VA prod. function	0.25 (0.01)	78% *
Mairesse-Hall (1994)	France 1232 firms	1981-89	VA prod. Function with ind dummies	0.176 (0.004) (corr.)	75% *
	US 1073 firms	1981-89	Prod function with ind dummies	0.173 (0.013)	28% *
Bartelsman et al (1996)	Netherlands ~200 mfg firms	1985, 89, 93	Prod function	0.006 to 0.014 (uncorr.) 0.018 to 0.033 (corr.)	
			VA prod. function	0.008 to 0.043 (uncorr.) 0.046 to 0.099 (corr.)	
Harhoff (1998)	Germany 443 mfg firms	1979-89	Prod function	0.14 (0.01) (uncorr.) 0.11 (0.01) (corr.)	71% *
Crépon-Duguet-Mairesse (1998)	France 6,145 firms	1990	VA prod function	0.12 (0.01)	
Los-Verspagen (2000)	U. S. 485 mfg firms	1974-93	VA prod. function, ECM	0.04 to 0.10	
Medda-Piga-Siegel (2003)	Italy 1008 firms, 689 firms	1992-95	treatment effect	0.026, 0.025	29%, 36%

Wang-Tsai (2003)	Taiwan 136 firms	1994-2000	VA prod function with random effects	0.20 (0.03) (corr.)	8% to 35% *
Bond-Harhoff-van Reenen (2005)	Germany 234 firms	1988-96	Prod. Function with common factor (dynamic); GMM-SYS	0.079 (0.042)	19%
	UK 239 firms	1988-96		0.065 (0.024)	38%
Mairesse-Mohnen-Kremp (2005)	France 488 firms	2000		0.043	16%
	France 351 firms	2000		0.028	27%
Griffith-Harrison-van Reenen (2006)	UK 188 mfg firms	1990-2000	VA Prod. Function	0.03 (0.01)	14% *
Rogers (2009)	UK 719 firms	1989-2000	VA prod function with R&D flow as input	0.12 to 0.16 (mfg; corr.) 0.12 to 0.23 (non-mfg; corr.)	40% to 58% (mfg) 53% to 108% (non-mfg)
Hall-Foray-Mairesse (2009)	US 1513 firms	2004-06	Prod function	0.096	23% *
Ortega-Argilés et al. (2009)	EU 532 firms	2000-05	Prod function with sector dummies	0.10	35%
Industry data					
Bartelsman (1990)	US 450 industries agg to 20 groups	1958-86	TFP with R&D stock Prod function	0.11 to 0.15 (0.03) 0.12 (0.03)	
Verspagen (1995)	4 hi tech inds 9 OECD countries	1973-88	Translog prod function with ind dummies	0.05 to 0.17 (uncorr.) 0.06 to 0.17 (corr.)	21% to 24% *

* computed using means or medians of the variables
** computed assuming an R&D/GDP ratio of 2% and an R&D flow/stock ratio of 1/7
Standard errors in parentheses
Production function dependent variable is gross sales unless otherwise noted.
uncorr = capital and labor not corrected for double counting of R&D inputs; corr. = corrected
Unless otherwise noted, estimates use uncorrected data.

Table 2b
R&D elasticities of output and rates of return to R&D
Temporal estimates on firm or industry-level data using the primal approach

Study	*Sample*	*Period*	*Type of estimation*	*R&D elasticity*	*R&D rate of return*
Firm data					
Griliches-Mairesse (1984)	U.S. 133 firms	1966-77	Within firm	0.09	64% *
Mairesse-Cuneo (1985)	France 390 firms	1974-79	Growth rates	0.022 (0.095)	0%
Griliches (1986)	US 652 firms	1966-77	Growth rates	0.12	
Hall (1993)	US ~1200 firms	1964-90	Within firm	0.06 (0.04)	22% *
Hall-Mairesse (1995)	France 197 firms	1980-87	Growth rates	0.05 to 0.17	23% (5%)
			Within firm	0.069 (0.035)	8% *
Mairesse-Hall (1994)	France 1232 firms	1981-89	VA prod function; within firm	0.068 (0.014)	33% *
			VA prod function; growth rate	0.080 (0.021)	
	US 1073 firms	1981-89	Prod function with hedonic deflator; within firm	0.170 (0.014)	150% *
			Prod function with hedonic deflator; growth rate	0.092 (0.026)	
Bartelsman et al (1996)	Netherlands ~200 mfg firms	1985, 89, 93	Long difference VA, long difference	0.051 (corr.) 0.104 (corr.)	
Harhoff (1998)	Germany 443 firms	1979-89	Within firm	0.09 (0.02) (corr.) 0.07 (0.02) (uncorr.)	66% *
			Long diff growth rates	0.10 (0.03) (uncorr.)	86% (17%)
Capron-Cincera (1998)	Multi-country 625 firms	1987-94	Growth rates Growth rates, GMM	0.32 (0.04) 0.13 (0.05)	
Los-Verspagen (2000)	U. S. 485 mfg firms	1974-93	VA prod. function	0.014	
Bond-Harhoff-van Reenen (2003)	Germany 234 firms	1988-96	GMM-DIF estimates	0.05	43% *
	UK 239 firms	1988-96	sectoral level	~0.015	20%
Griffith-Harrison-van Reenen (2006)	UK 188 mfg firms	1990-2000	GMM-SYS estimates	0.024 (0.011)	11% *
Dorazelski and	Spain	1991-99	OP estimation	0 to 0.018	

Jaumandreu (2008)	1800 firms	1991-99	VA; OP estimation	0.017 to 0.075
Industry data				
Bartelsman (1990)	US 450 industries agg to 20 groups	1958-86	TFP with R&D stock Prod function	0.10 to 0.12 (0.05) 0.18 (0.01)

** computed assuming an R&D/GDP ratio of 2% and an R&D flow/stock ratio of 1/7
Standard errors in parentheses
OP denotes Olley-Pakes estimates
The dependent variable is the log of sales unless otherwise noted.
uncorr = capital and labor not corrected for double counting of R&D inputs; corr. = corrected
Unless otherwise noted, estimates use uncorrected data.

Table 3
Estimated rates of return to R&D
Estimates from growth rates regressed on R&D intensity

Study	*Sample*	*Period*	*Type of estimation*	*R&D rate of return*
Plant data				
Clark-Griliches (1984)	US 924 business units	1971-80	Growth rates on R&D intensity	18% 20% (with ind dummies)
Lichtenberg and Siegel (1991)	US ~2000 firms	1972-81	TFP on R&D intensity	29% (2.4%)
Klette (1991)	Norway ~200 plants	1978-85	Growth rates on R&D intensity lagged	10 to 11% (corr.)
Firm data				
Odagiri -Iwata (1986)	Japan ~150 firms	1966-82	Growth rates on R&D intensity	17% to 20%
Griliches-Mairesse (1990)	U.S. 525 mfg firms	1973-80	Growth rates on R&D intensity	41% (9%)
	Japan 406 mfg firms	1973-80	Growth rates on R&D intensity	56% (23%)
Hall-Mairesse (1995)	France 197 mfg firms	1980-87	VA Growth rates	27% (6%) (corr.)
Bartelsman et al (1996)	Netherlands ~200 mfg firms	1985, 89, 93	4-yr growth rate	30% (corr. for double ctg)
			VA, 4-yr growth rate	173% (corr. for double ctg)
Harhoff (1998)	Germany 443 mfg firms	1979-89	Long diff growth rates	74% (11%) net 22% (4%) gross
Wakelin (2001)	UK 170 firms	1988-96	Growth rates, R&D flow intensity, ind dummies	29% (19%)
Rogers (2009)	UK 719 firms	1989-2000	VA prod function with R&D flow as input	40% to 58% (mfg) 53% to 108% (non-mfg)
Industry data				
Sveikauskas (2000)	US 22 asset classes (ind sectors)	1958-83	quality-adjusted TFP on R&D intensity	72.9%
Griffith-Redding-van Reenen (2004)	OECD 12 industries 12 countries	1974-90	VA Growth rates	47% to 67%

* computed using means or medians of the variables
** computed assuming an R&D/GDP ratio of 2% and an R&D flow/stock ratio of 1/7
Standard errors in parentheses
OP denotes Olley-Pakes estimates
Unless otherwise noted, the dep. var. is the annual growth of sales and the variable of interest is the R&D-to-sales ratio.
uncorr = capital and labor not corrected for double counting of R&D inputs; corr. = corrected
Unless otherwise noted, estimates use uncorrected data.

Table 4
Rate of return to R&D Estimates
Using the dual approach

Study	*Sample*	*Period*	*Model*	*Private rate of return estimate*
Firm data				
Bernstein (1988)	Canada 680 mfg firms	1978-81	Translog cost function and factor demand equations	12%
Bernstein and Nadiri (1990)	US 35 firms	1959-66	Factor demand equations with adj costs; from quadratic cost function	9% to 20%
Industry data				
Bernstein (1989)	Canada 9 industries	1963-83	Truncated translog cost function and factor demand eqs.	24% to 47%
Bernstein-Nadiri (1989)	U. S. 4 industries	1965-78	Factor demand equations with adj costs; from quadratic val function	7%
Mohnen-Lepine (1991)	Canada 12 mfg industries	1975, 77, 79, 81-83	Truncated translog cost function and variable factor demand eqs.	56% (5% to 275%)
Bernstein-Yan (1997)	Canada, Japan 10 industries	1964-82	Quadratic cost function plus capital factor demand eqs with adj costs	17.2% (Canada) 17.4% (Japan)
Bernstein (1998)	Canada and US 11 industries	1962-89	Quadratic cost function plus capital factor demand eqs with adj costs	16.4% (US) 12.8% (Canada)
Bernstein-Mohnen (1998)	Canada, Japan 11 industries	1962-86	Quadratic cost function plus capital factor demand eqs with adj costs	44% (US) 47% (Japan)
Country data				
Mohnen-Nadiri-Prucha (1986)	US, Japan, German mfg sectors	1965-77	Factor demand eqs derived from truncated quadratic cost function; capital adj costs nonseparable	11% (US) 15% (Japan) 13% (Germany)
Mohnen (1990)	Canadian mfg sector	1965-82	Factor demand eqs derived from truncated quadratic cost function; capital adj costs; IV est.	20%
Mohnen (1992b)	OECD 5 countries	1964-85	Factor demand eqs derived from truncated quadratic cost function; capital adj costs; GMM est.	6% to 9%
Nadiri-Kim (1996a)	US, Japan, Korea Total mfg	1975-90	Translog cost function and factor demand eqs.	12% (US) 12% (Japan) 19% (Korea)
Nadiri-Kim (1996b)	7 countries	1964-91	Translog cost function and factor demand eqs.	14% to 16%

"Truncated" means that some interaction terms were dropped as insignificant.

Where a range is given, it is the range of values obtained across industries.

Table 5
Elasticities and rate of return to own and others' R&D

				Own R&D		*External R&D*	
Study	*Sample*	*Period*	*Weighting scheme*	*Output elasticity*	*Rate of return*	*Output elasticity*	*Rate of return*
Plant data							
Adams-Jaffe (1996)	US chem sector 21,546 plant-yrs	1974-88	Spatial correlation in R&D product fields	0.05 (0.005)		0.07 (0.01)	
Firm data							
Jaffe (1988)	US 434 firms	1972-77	Spatial correlation in patent space	0.03 (0.01)	27% (0.8%)	0.10 (0.04)	
Bernstein (1988)	Canada 680 mfg firms	1978-81	Simple external sector-specific R&D stocks		12%		22%
Los-Verspagen (2000)	US 859 firms	1977-91	external R&D stocks; weighted by patent flows in several ways	0.0 to 0.07		0.33 to 0.68	
Industry data							
Griliches-Lichtenberg (1984a)	US 193 mfg industries	1959-78	Patent flows		11% to 31% (8%)		50% to 90% (36%)
Odagiri (1985)	Japan 15 mfg industries	1960-77	Inter-industry transactions		157% to 315%		-606% to 734%
Sterlacchini (1989)	UK 15 mfg industries	1945-83	Inter-industry transactions Innovation flows		12% to 20%		19% to 20% 15% to 35%
Goto-Suzuki (1989)	Japan 50 mfg industries	1978-83	Inter-industry transactions		26%		80%
Bernstein (1989)	Canada 11 mfg industries	1963-83	Simple external sector-specific R&D stocks		24% to 47%		29% to 94% (social)
Bernstein-Nadiri (1989)	U. S. 4 industries	1965-78	Simple external sector-specific R&D stocks		7%		9% to 13%
Mohnen-Lepine (1991)	Canada 12 mfg industries	1975, 77, 79, 81-83	Patent flows		56% (5% to 275%)		30% (2% to 90%)

Wolff-Nadiri (1993)	U.S. 19 mfg industries	1947, 58, 63, 67, 72,77	Inter-industry transactions		11%		14%
			Investments (capital inputs)		same		0%
Wolff-Nadiri (1993)	U.S. 50 industries	1947, 58, 63, 67, 72,77	Inter-industry transactions		19%		8%
			Investments (capital inputs)		same		9%
Verspagen (1997)	14 countries 22 industries	1974-93	Patents, imports and indirect imports; ECM model	0.10 (0.01)		0.03 (0.01) (domestic) 0.05 (0.01) (foreign)	
Bernstein-Yan (1997)	Canada and Japan; 10 industries	1964-82	Simple external sector-specific R&D stocks		17.2% (Canada) 17.4% (Japan)		62% to 183% (Canada) 9% to 56% (Japan)
Bernstein (1998)	Canada and US 11 mfg industries (separately)	1962-89	Simple external sector-specific R&D stocks		16.4% (US) 12.8% (Canada)		28% to 167% (US) 19% to 145% (Canada)
Bernstein-Mohnen (1998)	Canada and Japan; 11 industries	1962-86	Simple external sector-specific R&D stocks		44% (US) 47% (Japan)		47% (US) 0% (Japan)
Griffith-Redding-van Reenen (2004)	OECD 12 industries 12 countries	1974-90	industry-level TFP gap from frontier		47% to 67%		57% to 105%
Country data							
Mohnen (1990b)	Canadian mfg sector	1965-83	Hi-tech imports	0.01 (0.10)	20%	0.13 (0.09)	29%
Mohnen (1992b)	OECD 5 countries	1964-85	Simple foreign aggregate R&D stocks		6% to 9%		4% to 18%
Lichtenberg (1993)	53 countries	1960-85	None - external is own govt-funded	0.07 (0.02) pooled 0.07 (0.03) within			0.004 pooled 0.0 within

Coe-Helpman (1995)	22 countries	1971-90	Imports	0.22 (G7) 0.09 (other)	123% (G7) 85% (other)	0.06 (G7 to ROW)	32% (G7 to ROW)
Park (1995)	OECD 10 countries	1973-87	Imports	0.17 (0.06)		0.07 (G7 to all developing countries)	
Nadiri-Kim (1996b)	7 countries	1964-91	Imports		14% to 16%		6% to 11%
Coe-Helpman-Hoffmaister (1997)	North 22 countries South 77 countries	1971-90	Imports; especially of machinery & equipment			0.06 (0.02) (North to South)	
Kao et al (1999)	22 countries	1971-90	Imports; cointegration analysis	0.20 (G7) 0.09 (other)	120% (G7) 79% (other)	0.04 (G7 to ROW)	29% (G7 to ROW)
Keller (1997b)	22 countries	1971-90	Imports	0.13 (G7) 0.035 (other)		0.05 (G7 to ROW)	
van Pottelsberghe-Lichtenberg (2001)	13 countries	1971-90	Imports Inward FDI Outward FDI	0.05 (0.02) 0.08 (0.02) 0.06 (0.02)	68% (G7) 15% (other)	0.067 (0.013) 0.006 (0.004) 0.039 (0.009)	

Standard errors in parentheses

G7 = Canada, France, Germany, Italy, Japan, UK, US

Where a range is given, it is the range of values obtained across industries.