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R&D Incentives and Spillovers in a Two-Industry Model

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Abstract

This paper develops a two-industry model of R&D. A monopolist supplier sells an intermediate good to an oligopolistic buyer industry where firms compete in quantity and quality-enhancing R&D. The supplier can contribute to downstream product improvements by creating spillover knowledge which downstream firms use as a substitute for their own R&D efforts. Even if a market for R&D information fails to exist, the supplier may appropriate an indirect return on R&D for two reasons. Sufficiently high levels of spillover information lead to greater downstream product quality, and spillover information reduces the sunk cost of R&D necessary to enter the downstream industry. Both effects cause an expansion of downstream output and enhance the demand for the supplier's intermediate good.

Given sufficiently strong incentives for supplier R&D, the locus of R&D shifts partially from the downstream to the upstream industry. R&D intensities, technological opportunities, and the industry structure of the downstream industry are determined endogenously. The R&D behavior of supplier and buyer firms is characterized by switching equilibria, thereby providing support for the notion of distinct "technological regimes".

JEL Classification: O31

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1. Introduction

Contributions to the economics literature on technological progress often follow the assumption that private incentives for research and development (R&D) are predominantly shaped by industry-specific characteristics, such as the degree of competition, demand and appropriability conditions, and technological opportunities.[1] For example, most of the theoretical models are essentially based on stand-alone industries that have no connection to each other (Dasgupta and Stiglitz 1980; Lee and Wilde 1980; Levin and Reiss 1988; Loury 1979; Tandon 1984). Most empirical papers compare industries (or firms) with respect to their R&D intensity and use industry-specific measures as independent variables (Cohen and Levin 1989; Levin and Reiss 1988).[2]

There are two reasons why the results of these models can be deceiving. First, the analysis of stand-alone industries reflects the assumption that it is mostly horizontal (i.e. *intraindustry*) competition for rents that matters. While intraindustry effects are emphasized by this methodological approach, the importance of *interindustry* relationships and vertical interaction is often neglected. Consider for example an industry in which one firm has a dominant position due to its technological superiority. To alleviate the vertical distortion implied by the existence of a dominant player, firms in a supply sector try to support downstream competitors of the dominant firm in their attempts to improve their own product or process technologies. The suppliers' strategic incentives to affect the vertical distribution of rents may exceed the "stand-alone" incentives of firms in the downstream industry. Major contributions to technical change at the downstream level should then emerge in the upstream industry.

A second, but closely related problem of models based on stand-alone industries is that they neglect potentially important endogeneities. Typically, theoretical and in particular empirical work in this field is based on the assumption that the technological opportunities of firms in a given industry are determined exogenously, mainly as a function of technological contributions originating with firms in other sectors or institutions like government and university laboratories. This view has been followed by Levin and Reiss (1988; 1984), Levin et al. (1985), and Cohen and Levinthal (1989), among others. But the exogeneity of these measures of technological opportunity is a problematic assumption.[3] Firms in a supply sector may become technologically active precisely *because* they observe that their customers do not innovate on their own. As a consequence, the supplier firms may try to enhance the quality of their intermediate goods, thereby providing the downstream sector with new technological opportunities. Or suppliers may try to assist their customers by offering disembodied information

[1] A detailed discussion of these issues is presented by Cohen and Levin (1989).

[2] Among the few exceptions are Binswanger and Ruttan (1978), Jaffe (1986), and Mishina (1989).

[3] Doubts regarding the supposedly exogenous character of scientific knowledge have also been raised by Rosenberg (1982, p. 159) who concludes that "(...) powerful economic impulses are shaping, directing, and constraining the scientific enterprise."

that is cost-reducing or quality-enhancing (or both). In these cases, the technological opportunities faced by downstream firms are no longer exogenous, but endogenously determined.

This view is supported by numerous case studies in which strategically motivated R&D contributions by vertically related firms are evident. For example, a detailed study of marketing practices relating to new materials has been provided by Corey (1956). In his case studies, Corey analyzes the efforts undertaken by materials suppliers to enhance the demand for their commodity products. The production processes for products like vinyl flooring, several fiberglass products (like fiberglass-reinforced pipe), aluminum bearings, vinyl film, and plastic toys were in many cases developed with considerable assistance from the leading materials suppliers. These firms also undertook advertising efforts and assisted downstream manufacturers in maintaining product quality. Peck (1962) notes that aluminum producers had a major impact on the design of new aluminum-using products. Graham and Pruitt (1990) present a detailed historical study of Alcoa's efforts to develop aluminum beverage cans. While Alcoa itself never integrated into can production, it contributed with major R&D efforts to the development of aluminum cans for beverages. Two other detailed industry studies have been provided by VanderWerf (1990) who studies the occurrence of major innovations since World War II in two technical processes: thermoplastics forming and molding and applications of industrial gases. In both processes significant amounts of commodity materials are used. Materials suppliers were identified as the innovators in roughly one third of the cases. VanderWerf suggests that the suppliers apparently did not charge licensing fees for their innovations. They profited from their innovative efforts by experiencing enhanced demand for their commodity.[4]

This paper tries to explore some of these issues by studying the interdependence of R&D incentives in two vertically related industries. I develop a two-industry model of technical change in which R&D activities earmarked to enhance product quality in the downstream industry are distributed across supplier and buyer firms. A monopolist supplier faces an oligopolistic buyer industry in which firms employ a factor of production delivered by the supplier. The downstream firms compete in quantities and in quality-enhancing R&D. Contrary to previous models of R&D, I assume that the oligopolistic downstream firms have access to two different kinds of R&D. The first type can be characterized as idiosyncratic, i.e. specific to the firm's product and production methods. The second type of R&D is generic in that all firms can make use of R&D results of this form, should they ever spill over across firms or should such R&D be provided by external contributors.

[4] The arguments made in this paper may also be applied to a setting in which large buyer firms face a number of competitive suppliers. For example, Leenders and Blenkhorn (1988) provide case studies in which large buyer firms seek to induce technical change among their suppliers by providing them with R&D results.

With an *exogenously* given downstream industry structure, the downstream R&D incentives may be insufficient from the supplier's perspective. Producing a substitute for the downstream firms' generic R&D, the supplier can affect downstream product quality by i) increasing the equilibrium level of generic R&D effectively used in product improvements, and ii) by enhancing the productivity of idiosyncratic R&D. As a consequence of the supplier's R&D contribution, downstream output expands and the supplier's factor demand is shifted to higher levels. Given that the supplier sells its output with a non-zero price-cost margin, its profit gross of R&D expenditures is enhanced.

When downstream industry structure is determined *endogenously* as a consequence of the sunk cost of R&D, the supplier has the additional incentive to generate interindustry spillovers in order to facilitate entry into the downstream industry. Lowering the barriers to entry into the downstream industry allows a comparatively greater number of firms to enter than would be sustainable in an equilibrium without supplier R&D involvement. Greater competition in the downstream industry may affect R&D incentives negatively, but this effect is dominated by the output expansion caused by more vigorous competition among downstream firms. Again the supplier faces increased factor demand which allows the upstream firm to appropriate an indirect return on its R&D investment.

Independent of whether industry structure is modelled exogenously or endogenously, the equilibrium R&D intensities and measures of technological opportunities are contingent on the interaction between upstream and downstream R&D incentives. The transition between a regime in which the supplier is actively contributing own R&D results and one in which only downstream firms contribute to quality-enhancing R&D is *discontinuous* in this model. The switching equilibria characterized in the paper can therefore be interpreted as support for the notion of distinct "technological regimes."

Some institutionally oriented researchers have pointed out that innovation in various industries can be categorized according to a few distinct "technological regimes." Von Hippel (1982; 1988), for example, focuses on various functional roles that firms in a vertical chain can play and distinguishes between supplier innovation, manufacturer innovation, and user innovation. Pavitt (1984) proposes a taxonomy of three distinct patterns of innovation: supplier dominated innovation, innovation that depends on large-scale production, and science-based innovation. Acs and Audretsch (1987; 1988) follow a suggestion by Winter (1984) and distinguish two regimes, one in which small firms are the predominant innovators and one in which new technologies are mostly generated by larger enterprises. So far, there has been no formal theoretical work to analyze the determinants of such "technological regimes". This paper applies the concept of technological regimes to vertical relationships and formalizes it in a model of product innovation.

The remainder of the paper is organized in four sections. Section 2 describes the basic model and characterizes the equilibria in the two industries under consideration. Section 3 studies extensions of the simple two-industry model. I analyze the implications of intraindustry spillovers and the case of a downstream industry with endogenously determined industry structure. Some numerical examples complement the theoretical analysis. Section 4 concludes with some suggestions for further theoretical and empirical work.

2. A Model of R&D with Strategic Spillovers

The point of departure for this paper is a "non-tournament" model of product innovation based on earlier models developed by Levin and Reiss (1988), Dixit and Stiglitz (1979) and Koenker and Perry (1981). To simplify the exposition I will use a stylized setup and assume initially that industry structure is given exogenously.[5]

There are two industries in this model. Consider first the downstream sector in which oligopolistic firms manufacture and sell a consumer product. Downstream firms compete in quality-enhancing R&D and in quantities and receive a factor of production at unit price u from an upstream monopolist. By choosing an optimal factor price the supplier can affect downstream R&D incentives. Furthermore, I assume that the supplier can engage in R&D and generate spillover knowledge which functions as a (partial) substitute of the downstream firms' R&D efforts. Spillover production is a second strategic action for the supplier in this model, since the existence of interindustry spillovers affects the R&D incentives of downstream firms. In the following three subsections I first provide a more detailed description of the model, then derive explicit solutions characterizing the equilibrium in the downstream industry as a function of the supplier's behavior, and finally determine the supplier's optimal choice of factor price and R&D spillovers.

2.1 The Basic Model

I assume that consumers of the downstream product are characterized by an aggregate utility function U(.) of the form

(1) $$U(G) = U(w_1q_1 + w_2q_2 + \dots + w_Nq_N)$$

where $U'(.)>0$ and $U''(.)<0$. N indicates the number of firms in the downstream industry, q_i is the output of firm i in this industry ($i = 1, 2, \dots, N$) and w_i reflects the

[5] The implications of endogenously determined sunk cost for industry structure and R&D incentives are discussed later.

quality of firm i's product. The variable G will indicate the quality-weighted sum of the downstream firms' outputs. Q will denote the unweighted sum of outputs, i.e. the industry's total production.

The utility specification (1) implies an inverse demand function $p_i(G,q_i,w_i)$ of the form

$$(2) \qquad p_i(G, q_i, w_i) = \frac{\partial U}{\partial G}\frac{\partial G}{\partial q_i} = U'(G) \cdot w_i \quad .$$

To obtain closed-form solutions I follow Levin and Reiss (1988) and Dasgupta and Stiglitz (1980) and use specific functional forms. In particular, I assume that the aggregate utility function is given by

$$(3) \qquad u(G) = \frac{\sigma}{1-\varepsilon}\left(\sum_{i=1}^{N} w_i q_i\right)^{1-\varepsilon} \qquad (\sigma, \varepsilon > 0) .$$

Firm i's inverse demand function $p_i(G,q_i,w_i)$ is then given by

$$(4) \qquad p_i(G,q_i,w_i) = \sigma\left(\sum_{i=1}^{n} w_i q_i\right)^{-\varepsilon} w_i \qquad .$$

The parameter ε in this specification is the inverse of the elasticity of demand with respect to price. σ is a scaling parameter indicating the size of the market.

Each downstream firm i can improve its own product quality w_i by making R&D investments. I assume that firms can exercise two complementary types of R&D activities. The first type of R&D effort is completely idiosyncratic, i.e. specific to the firm's variety of the differentiated product or its production process. Investments of this sort will be denoted by z_i. The second kind of R&D effort is completely generic, i.e. its results could theoretically be employed by any of the firms in the industry. However, I will assume initially that each firm protects its generic knowledge perfectly so that no spillovers occur.[6] The generic R&D investments will be denoted by x_i.

Both types of R&D investments contribute in a deterministic way to product quality, i.e. $w_i=w_i(z_i,x_i)$ where $\partial w_i/\partial x_i>0$, $\partial w_i/\partial z_i>0$, $\partial^2 w_i/\partial x_i^2<0$ and $\partial^2 w_i/\partial z_i^2<0$. Furthermore, I assume that $\partial^2 w_i/\partial x_i \partial z_i>0$, i.e. both types of R&D are complementary

[6] In section 3 I discuss the effect of intraindustry spillovers and their relationship to supplier R&D incentives.

in the sense that greater investment in either type will enhance the marginal effect of the other type of R&D investment on product quality.[7]

This specification attempts to reconcile two diverging opinions which are both widely held among students of technical change as Nelson (1980; 1982) has pointed out. On the one hand, it is often alleged that information held by a firm has public goods characteristics, i.e. if not maintained as a secret, the information will spill over to other firms, thus causing a failure of appropriability (Spence 1984; Tandon 1983). At the same time, many researchers have pointed out that knowledge has idiosyncratic qualities, too. It may be specifically tailored to a given context, for example to a unique production environment or product type, or it may be "tacit" in Polanyi's (1958) sense and therefore hard to encode and transmit. Detailed discussions of the cost of information transfer have been provided by von Hippel (1990), Kogut and Zander (1989), Nelson (1980), and Teece (1977).

In the specification chosen in this paper, a firm's knowledge or information base consists of both components, but depending on the functional form and parameterization chosen, either component may dominate the other. For example, if the marginal effect of idiosyncratic R&D activities is very small at all levels of R&D investment, then the conceptualization of firm's knowledge is similar to the one suggested by Spence (1984) and Dasgupta and Stiglitz (1980). Conversely, if only completely idiosyncratic knowledge is productive, then even a full revelation of the firm's information will not have any adverse effects on economic appropriability, since competitors cannot employ the idiosyncratic R&D results generated by another firm.[8]

Again it will be necessary to appeal to specific functional forms in order to derive closed-form solutions of the model. A convenient iso-elastic specification of the relationship between product quality w_i and R&D investments z_i and x_i is given by

$$(5) \qquad w_i(z_i,x_i) = z_i^{\beta} x_i^{\alpha} \qquad (\alpha, \beta \geq 0).$$

The parameters α and β are the (constant) elasticities of product quality with respect to generic and idiosyncratic R&D investments. Note that both types of R&D are productive here as long as the respective elasticities are greater than zero. By choosing

[7] The assumed complementarity between idiosyncratic and generic forms of R&D also reflects the concerns of Cohen and Levinthal (1989) who point out that own R&D may enhance the firm's capacity to absorb any externally available R&D.

[8] This conceptualization of a firm's knowledge also has implications for the modelling of the social choice problem. Typically, theoretical models of technical change consider all private R&D wasteful duplication and depict the social problem as choosing some socially optimal R&D investment. The resulting information is then transferred to all firms (at zero cost) and employed by them. Given the possibility of idiosyncratic production environments or product differentiation, this idea may be unrealistic and misleading. In this model wasteful duplication occurs only with respect to the generic component of a firm's knowledge pool, since by assumption the results from idiosyncratic R&D have no value if transferred to another firm.

different elasticity parameters, one can approximate the characteristics of quality-enhancing information, i.e. from highly idiosyncratic to relatively generic knowledge.

So far, the specification of product quality would not allow us to study the effect of upstream R&D efforts on the downstream industry's equilibrium. Extending the specification of product quality to include the effect of interindustry spillovers, it is assumed that the upstream supplier can produce a perfect substitute for the downstream firms' generic R&D investment. If the upstream supplier's R&D investment is y, then the downstream firms' product quality is given as a function of R&D investments x, z, and y as

(6) $w_i(z_i,x_i;y) = z_i^{\beta}(x_i+y)^{\alpha}$.

This relationship can be given several interpretations, but I will only focus on two that seem particularly interesting. First, one may view y as a measure of disembodied knowledge, provided to downstream firms by the supplier.[9] In all likelihood, the market for this knowledge will be imperfect (Arrow 1962; Caves, Crookell et al. 1983) so that the supplier cannot price the R&D information separately. The reader may think of y as an *intentionally produced interindustry spillover* in this case.[10] Alternatively, the upstream R&D investment y could represent the embodiment of technological change in the factor supplied to downstream firms by the monopolist.

The production technology for the new downstream product is assumed to be given and independent of the level of product quality.[11] In particular, I assume that marginal cost of production c is a function of factor input prices u and v, where u is the unit price of the monopolist supplier's intermediate good and v is the price of all other inputs. v is assumed to be constant. Hence,

(7) $c = c(u,v)$.

This unit cost function is assumed to allow for substitution between the two factors of production with constant elasticity of substitution μ and to be homogeneous of degree one in factor prices.[12] Note that substitution between the two factors implies production with variable proportions and a concomitant vertical distortion (Tirole 1988). Hence, the supplier in the model below would have incentives to integrate ver-

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9 See the introduction for case studies supporting this view.

10 Modelling y as a substitute of the downstream firms' own R&D efforts can be justified on the basis of empirical studies. Bernstein (1988) and Bernstein and Nadiri (1988) find in several tests that interindustry spillovers are substitutes for the firm's own R&D investments.

11 An analogous two-sector model can be developed for cost-reducing R&D. See Harhoff (1991a).

12 For the derivations that follow, the elasticity of substitution μ need not be constant at all price levels u and v. The assumption is made here to avoid unnecessarily complex algebraic expressions. For the same reason I do not write marginal cost c explicitly as a function of μ.

tically into downstream production if integration were costless. I assume that the latter is not the case, but as usual in vertical models, the integration alternative is not modelled explicitly.[13]

2.2 Equilibrium in the Downstream Industry

Downstream firms take upstream decisions regarding spillover production y and factor price u as given. The downstream oligopolists compete in quantities q_i and R&D investments x_i and z_i. A downstream firm i maximizes its profits by choosing q_i, z_i, and x_i according to the maximization problem

$$(8) \quad MAX_{\{q_i,z_i,x_i\}} [p_i(\sum_{j \neq i} w(z_j,x_j;y)q_j + w(z_i,x_i;y)q_i) - c(u,v)]q_i - z_i - x_i$$

$$\text{s.t. } x_i, z_i, q_i \geq 0.$$

Note that the number of firms N has to be small enough to exclude industry structures where any firm would make a negative profit:

$$(9) \quad [p_i(\sum_{j=1}^{N} w_j(z_i^*, x_j^*; y) q_j^*) - c(u, v)] q_i^* - z_i^* - x_i^* \geq 0 \quad \forall i \in \{1, 2, ..., N\} .$$

The first-order conditions for the unconstrained maximization problem (8) are

$$(10) \quad p_i(.) - c(u, v) + \frac{\partial p_i(.)}{\partial q_i} q_i = 0 \quad ,$$

$$(11) \quad \frac{\partial p_i(.)}{\partial z_i} q_i - 1 = 0 \quad ,$$

$$(12) \quad \frac{\partial p_i(.)}{\partial x_i} q_i - 1 = 0 \quad , \forall i \in \{1,2,...,N\} \quad .$$

In the following analysis I will focus on symmetric Nash equilibria. Indices indicating firms will be suppressed. Clearly, the equilibrium solutions will be a function of the upstream monopolist's choice variables u and y. Let q*(y,u), x*(y,u), and

[13] On empirical grounds this seems justified. Corey (1956) and VanderWerf (1990) find only rare cases of vertical integration in their studies. One may also appeal to the monitoring costs associated with hierarchical organizations to justify the assumption that vertical integration is not a feasible option for the monopolist supplier.

$z^*(y,u)$ denote the downstream firms' choices of quantities and of generic and specific R&D investments, given that the monopolist supplier charges a unit factor price u and produces interindustry spillovers y.[14] Furthermore, let $Q^*(y,u) = Nq^*(y,u)$ denote the downstream industry's total output as a function of the upstream choices.

Solving the first-order conditions to derive closed-form solutions one has to take into account that the downstream firms' choice of generic R&D investment x may be characterized by a corner solution. If the supplier makes a sufficiently high investment in generic R&D, then downstream firms will have no incentive to invest in this type of research and will be contempt to undertake idiosyncratic R&D only. Hence, the solutions will be contingent on the extent of spillovers y. Let $x^*(0,u)$ denote the level of generic R&D investment that a downstream firm chooses if the upstream monopolist does not engage in spillover production, i.e. y=0. Then one obtains by transforming the first-order conditions and using the parametric specifications in (4) and (6)

$$(13)\quad p\,(1 - \frac{\varepsilon}{N}) = c(u,v)$$

$$(14)\quad x^*(y,u) = \begin{cases} [\sigma(1-\varepsilon/N)\,(\alpha/N)^{\varepsilon}\,(\beta/\alpha)^{\beta(1-\varepsilon)}c(.)^{\varepsilon-1}]^{1/[\varepsilon-(\alpha+\beta)(1-\varepsilon)]} - y & \text{if } y<x^*(0,u) \\ 0 & \text{if } y\geq x^*(0,u) \end{cases}$$

$$(15)\quad z^*(y,u) = \begin{cases} [\sigma(1-\varepsilon/N)\,(\beta/N)^{\varepsilon}\,(\alpha/\beta)^{\alpha(1-\varepsilon)}c(.)^{\varepsilon-1}]^{1/[\varepsilon-(\alpha+\beta)(1-\varepsilon)]} & \text{if } y<x^*(0,u) \\ [\sigma(1-\varepsilon/N)\,(\beta/N)^{\varepsilon}\,y^{\alpha(1-\varepsilon)}c(.)^{\varepsilon-1}]^{1/[\varepsilon-\beta(1-\varepsilon)]} & \text{if } y\geq x^*(0,u). \end{cases}$$

Total output of the downstream industry as a function of y and u is given by

$$(16)\quad Q^*(y,u) = \begin{cases} [\sigma(1-\varepsilon/N)\,(\beta/N)^{\beta(1-\varepsilon)}\,(\alpha/N)^{\alpha(1-\varepsilon)}\,c(.)^{(\alpha+\beta)(1-\varepsilon)-1}]^{1/[\varepsilon-(\alpha+\beta)(1-\varepsilon)]} & \text{if } y<x^*(0,u) \\ [\sigma(1-\varepsilon/N)\,(\beta/N)^{\beta(1-\varepsilon)}\,y^{\alpha(1-\varepsilon)}c(.)^{\beta(1-\varepsilon)-1}]^{1/[\varepsilon-\beta(1-\varepsilon)]} & \text{if } y\geq x^*(0,u) \end{cases}$$

Note from result (14) that as long as $0<y<x^*(0,u)$, both the supplier and the downstream firms will contribute to generic R&D. The downstream firm's response function $x^*(y,u)$ is linearly decreasing in y as long as $y<x^*(0,u)$. Since x and y are

[14] To economize on notation the dependence on the functional form of c(u,v) will be suppressed here.

perfect substitutes, total generic R&D investment y+x*(y,u) will sum up to the level of x*(0,u) which a downstream firm would choose were there no supplier involvement. Also, as long as y<x*(0,u), the downstream firms' decisions with respect to idiosyncratic R&D z*(y,u) and output q*(y,u) will *not* be contingent on the level of upstream R&D investment, as results (13) and (14) indicate. Upstream R&D investments simply "subsidize" downstream R&D without affecting the level of industry output or product quality.

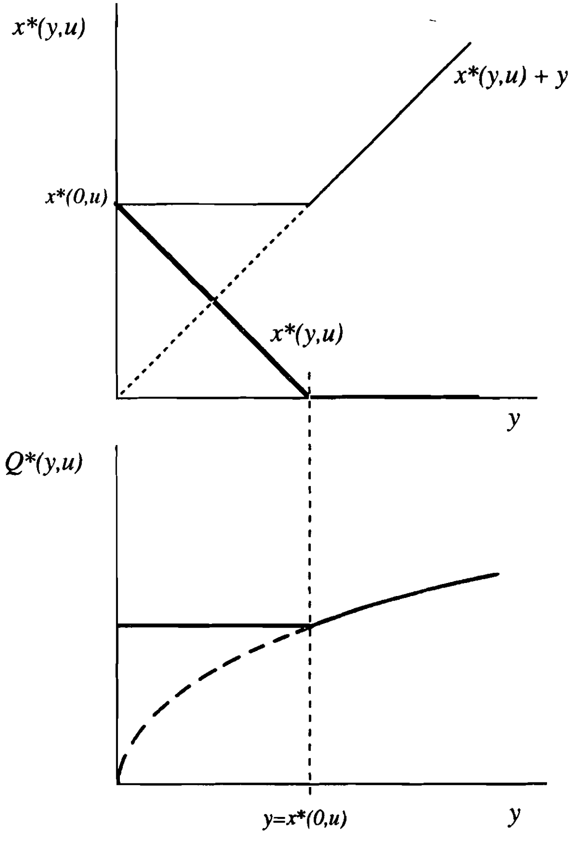

Figure 1
Downstream R&D Investments x* and Industry Output Q* as a Function of Supplier R&D y

$z^*(.)$ and $q^*(.)$ will become contingent on the level of y once the critical level of generic R&D $x^*(0,u)$ is exceeded by the supplier's R&D investment. By choosing its factor price u and its research investment y, the upstream firm can effectively determine whether the corner solution or the interior solution will prevail in the downstream industry. These aspects of the solutions are illustrated in Figure 1.

For (14), (15), and (16) to characterize an equilibrium one has to suppose that $\varepsilon>(\alpha+\beta)(1-\varepsilon)$. The following derivations take this assumption as given.[15]
The above results can be used to derive the R&D intensities

$$(17) \quad Z^*(y,u) = \frac{z^*(y,u)}{pq^*(y,u)} = \beta(1-\frac{\varepsilon}{N})$$

and

$$(18) \quad X^*(y,u) = \frac{x^*(y,u)}{pq^*(y,u)} = \begin{cases} \alpha(1-\frac{\varepsilon}{N}) & \text{if } y=0 \\ 0 & \text{if } y\geq x^*(0,u) \end{cases} .$$

Equation (17) gives an expression for the intensity of idiosyncratic research Z^* of the industry, given that the number of firms is equal to N. Equation (18) states the corresponding result for the intensity of generic R&D efforts X^*.[16]

Using the results (13), (17), and (18) and inserting them in condition (9), one can show that the number of firms N has to satisfy

$$(19) \quad \begin{array}{ll} \varepsilon \leq N \leq \varepsilon/(\alpha+\beta) + \varepsilon & \text{if } y=0 \text{ and} \\ \varepsilon \leq N \leq \varepsilon/\beta + \varepsilon & \text{if } y\geq x^*(0,u). \end{array}$$

The restriction $\varepsilon\leq N$ in (19) follows directly from inspection of result (13) while the second restriction is a direct implication of the restriction to positive profits (9).

For the discussion of the supplier's maximization problem, it will be helpful to study some comparative statics of these results. Note from (14) and (15) that the downstream firm's R&D investments $x^*(.)$ and $z^*(.)$ are decreasing in the level of production cost $c(.)$ as long as demand is elastic (i.e. $1/\varepsilon<1$). With inelastic demand

[15] This assumption ensures that the profit function of a firm is locally concave. See Dasgupta and Stiglitz (1980) in their Appendix I.

[16] By comparing (17) to (18) in the case of $y<x^*(0,u)$ one can also see that the composition of the downstream firm's R&D budget will be a simple function of the productivity of both types of R&D, i.e. $x^*/z^* = \alpha/\beta$, which is not surprising given the Cobb-Douglas form of the quality specification. Note that the decomposition of total R&D into two components is in all likelihood not observable, but it provides a convenient conceptual tool.

($1/\varepsilon>1$) the effect of production cost is the opposite and higher cost levels will yield greater R&D investments. The effect of production cost c(.) on output is *not* contingent on the elasticity of demand, however. Inspection of result (16) shows that the industry's output will be strictly decreasing in c(.).

The results also predict that the incentives of oligopolistic producers to invest in the improvement of their own products declines with the extent of competition, i.e. with the number of firms in the industry. This is a typical conclusion emerging from non-tournament models of R&D and innovation (Dasgupta and Stiglitz 1980; Levin and Reiss 1988).

2.3 Equilibrium in the Upstream Industry

The supplier anticipates the behavior of downstream firms and takes into account that its pricing and R&D behavior will affect the downstream industry's output and thus the demand for the factor of production sold to downstream firms by the monopolist. Thus the supplier is a Stackelberg leader in this model.

Using Shepard's Lemma, one can derive total downstream factor demand f(y,u) for the monopolist supplier's good as

(20) $f(y,u) = \partial c(u,v)/\partial u \; Q^*(y,u)$.

Thus the supplier solves the maximization problem

(21) $MAX_{\{y,\, u\}} \; \Pi_S(y,u) = (u-c_S) \; \partial c(u,v)/\partial u \; Q^*(y,u) \; - y$
s.t. $y, u \geq 0$

where c_S is the supplier's constant marginal cost of production. To derive the possible equilibrium solutions of this problem it is helpful to study two properties of the function $Q^*(y,u)$ in result (16).

Proposition 1

The supplier will never choose to make an R&D investment $y>0$ if downstream demand is inelastic ($\varepsilon>1$).

Proof: This result follows directly from observing that upstream R&D y has a negative effect on downstream industry output in (16) whenever $\varepsilon>1$. Factor demand will be shifted to lower levels if the supplier were to invest any amount $y>0$.•

As a second implication, note that the supplier will have no incentive to choose any level of R&D $0<y<x^*(0,u)$, since downstream output and therefore factor demand

are not affected while the cost of doing R&D is partially shifted to the upstream sector.

Proposition 2:

With exogenously given industry structure and supplier R&D y being a perfect substitute of downstream generic R&D, there can be no equilibrium solution in which downstream firms and the supplier contribute to generic R&D simultaneously. The supplier will never invest an amount $0<y<x^*(0, u)$, i.e. he invests either $y=0$ or $y>x^*(0,u)$.

Proof: Suppose otherwise, i.e. at some factor price u the supplier invests y where $0<y<x^*(0,u)$ such that the interior solution to the maximization problem in (8) prevails. But then the supplier would always be better off to let downstream firms undertake all generic R&D. Since output and product quality are not affected by the supplier's investment (see Fig. 1), the supplier's profit *gross* of R&D is not affected, but he incurs the cost of R&D. Thus investing y where $0<y<x^{**}(0,u)$ cannot be optimal.•

Proposition 2 implies that either the downstream firms will perform all of the generic R&D or the supplier will perform all of the generic R&D. Thus the first candidate for an equilibrium solution is characterized by $y=0$. In this case only downstream firms invest in generic R&D and the supplier simply chooses the factor price u such as to maximize upstream profits. Moreover, there is a second potential equilibrium in which only the supplier invests in generic R&D such that $y \geq x^*(0,u)$, i.e. downstream generic R&D is completely crowded out. Clearly, the supplier will choose the solution that maximizes profits. The conditions under which one or the other equilibrium will prevail can be then found by comparing the supplier's profit implied by the two candidate equilibria.

Case 1 - No Generic R&D Investment by the Supplier (y=0)

Let the optimal factor price be denoted u* in this case and consider the upstream monopolist's factor pricing decision. The corresponding first-order condition of this maximization problem can be transformed to yield

$$(22) \quad \frac{u^* - c_S}{u^*} = \left(\frac{\partial f(y,u)}{\partial u} \frac{u}{f(y,u)} \right)^{-1} \Bigg|_{u=u^*,\, y=0}$$

where the RHS in (22) is the inverse of the elasticity of factor demand with respect to the factor price u. Let this elasticity be denoted δ^*. One can show (Harhoff 1991b) that δ^* can be written as

$$(23)\quad \delta^* = k^* \frac{1-(\alpha+\beta)(1-\varepsilon)}{\varepsilon-(\alpha+\beta)(1-\varepsilon)} + (1-k^*)\,\mu$$

where k^* is the share of the monopolist's factor of production in downstream production cost

$$(24)\quad k^* = \frac{\partial c(u,v)}{\partial u} \frac{u}{c(u,v)} \Big|_{u=u^*}$$

and μ is the elasticity of substitution between the two factors.[17]

The result in (23) is a generalization of previously derived expressions for the elasticity of derived demand (e.g. Waterson (1980)). If we simply neglect the possibility of quality enhancing R&D by setting α and β equal to zero, then we obtain the commonly known form of this relationship, i.e. $\delta = k\varepsilon^{-1} + (1-k)\,\mu$.[18]

Allowing for technical change, differentiation of the right-hand side in equation (23) shows that δ^*, the elasticity of factor demand with respect to factor price u, is strictly increasing in α and β. *The higher the downstream R&D elasticities, the more profitable it will be for the supplier to soften its pricing policy in order to shift factor demand to higher levels.*[19] This relationship indicates that the monopolist supplier - in order to increase demand spillovers from downstream innovation - will have to relinquish some of its (static) market power, the more so the greater the R&D elasticities in the buyer industry.

Using the results in (16) and (23), the supplier's profit $\Pi_S(0,u^*)$ is now given by

$$(25)\quad \Pi_S(0,u^*) = \frac{k^*}{\delta^*} \left[c(u^*,v)^{\varepsilon-1}\sigma(1-\varepsilon/N)\,(\alpha/N)^{\alpha(1-\varepsilon)}(\beta/N)^{\beta(1-\varepsilon)}\right]^{1/[\varepsilon-(\alpha+\beta)(1-\varepsilon)]}$$

$$= \frac{1}{\delta^*}\; k^*\, c(u^*,v)\, Q^*(0,u^*) \quad .$$

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[17] Details on the elasticity results are described in Harhoff (1991b).

[18] See Allen (1938, p. 372-375), Bronfenbrenner (1966), Sato and Koizumi (1970), and Waterson (1980). For an empirical test of the relationship between δ and k ("Marshall's Third Law") see Bradburd (1981).

[19] With elastic demand a softer pricing strategy promotes downstream R&D incentives. Downstream R&D will have a particularly strong effect on factor demand whenever the R&D elasticities of product quality are comparatively large. Conversely, with inelastic demand *higher* factor prices encourage R&D, but R&D itself affects factor demand negatively.

The second equality in (25) shows that the supplier's profit can be written as the product of its sales $k^*c(.)Q^*(.)$ and $1/\delta^*$, the inverse of the elasticity of factor demand which measures the supplier's return on sales (gross of fixed cost). Note that if there are negligible opportunities for product improvements in the downstream industry (α and β converge to zero), the result in equation (25) simplifies to the supplier profits obtained in a world without technological progress.

Case 2 - No Generic R&D Investment by Downstream Firms ($x^*=0$)

Once the supplier chooses an R&D investment $y \geq x^*(0,u)$, the downstream equilibrium is determined by a corner solution. Downstream firms have no incentive to invest in the generic form of research anymore and will engage in idiosyncratic R&D only. The output and R&D response functions in (16) and (35) are now a function of y, the supplier's R&D investment and of production cost c(.) (which are a function of the supplier's factor price u).

The supplier's R&D and pricing decisions for this case can be found by evaluating the first-order conditions of the maximization problem (22), assuming the existence of a downstream corner solution equilibrium. Let y^{**} denote the the optimal R&D investment and u^{**} denote the optimal factor price.[20] Then

$$(26)\quad \frac{u^{**}-c_S}{u^{**}} = \frac{1}{\delta^{**}}$$

where δ^{**} - in analogy to (23) - is given by

$$(27)\quad \delta^{**} = k^{**}\,\frac{1-\beta(1-\varepsilon)}{\varepsilon-\beta(1-\varepsilon)} + (1-k^{**})\,\mu \quad .$$

and k^{**} is the monopolist supplier's cost share in downstream production, given that he charges a factor price u^{**}. Note that the elasticity of factor demand in (27) is reduced in comparison to the previously derived one in (23). Hence, one effect of generic R&D being shifted to the upstream sector is that the supplier's optimal factor price will be higher, ceteris paribus. This change is a direct consequence of the incentive effects of factor pricing discussed above. Once downstream firms stop to invest in generic R&D, the supplier will no longer provide the respective incentives.

Evaluating the first-order condition for the supplier's optimal R&D investment (again for the case of a downstream corner solution) yields

[20] It is straight-forward to demonstrate that the supplier's maximization problem is well-defined in this case.

$$(28)\quad y^{**} = \left[\left(\frac{k^{**}}{\delta^{**}}\,\frac{\alpha(1-\varepsilon)}{\varepsilon-\beta(1-\varepsilon)}\right)^{\varepsilon-\beta(1-\varepsilon)} \left[c(u^{**},v)^{\varepsilon-1}\,\alpha(1-\varepsilon/N)\,(\beta/N)^{\beta(1-\varepsilon)}\right]^{1/[\varepsilon-(\alpha+\beta)(1-\varepsilon)]}\right.$$

which can also be written as

$$y^{**} = \frac{k^{**}}{\delta^{**}} c(u^{**},v)\ Q^*(y^{**},u^{**})\ \frac{\alpha(1-\varepsilon)}{\varepsilon-\beta(1-\varepsilon)}\ .$$

Using the last result one can show that once all generic R&D is done by the supplier, *upstream* R&D intensity is a simple function of the elasticity of factor demand (measuring the supplier's return to sales) and *downstream* parameters ε, α, and β:

$$(29)\quad Y^{**} = \frac{y^{**}}{u^{**}\cdot f(y^{**},u^{**})} = \frac{1}{\delta^{**}}\,\frac{\alpha(1-\varepsilon)}{\varepsilon-\beta(1-\varepsilon)}\ .$$

Note that the supply sector's R&D intensity in (29) is increasing in α and β, the elasticities of *downstream* product quality with respect to idiosyncratic and generic R&D investments. Using result (28), we can write the supplier's profit $\Pi_S(y^{**},u^{**})$ as

$$(30)\quad \Pi_S(y^{**},u^{**}) = \frac{k^{**}}{\delta^{**}}\left[\alpha(1-\varepsilon/N)\,(\beta/N)^{\beta(1-\varepsilon)}\left(\frac{k^{**}}{\delta^{**}}\,\frac{\alpha(1-\varepsilon)}{\varepsilon-\beta(1-\varepsilon)}\right)^{\alpha(1-\varepsilon)} \times\right.$$

$$\left.\times\, c(u^{**},v)^{\varepsilon-1}\right]^{1/[\varepsilon-(\alpha+\beta)(1-\varepsilon)]}\left(1-\frac{\alpha(1-\varepsilon)}{\varepsilon-\beta(1-\varepsilon)}\right)$$

<u>Comparison of the Two Equilibria</u>

Formally, a *necessary and sufficient* condition for a supplier R&D investment to occur can be derived by comparing the supplier's profits $\Pi_S(0,u^*)$ and $\Pi_S(y^{**},u^{**})$.The condition[21]

$$(31)\quad \Pi_S(y^{**},u^{**}) > \Pi_S(0,u^*)$$

can be transformed to

[21] Note that I assumed the existence of the corner solution for the derivation of results (28) and (29). However, if condition (31) is satisfied, then $\Pi_S(y^{**},u^{**})>\Pi_S(0,u^*)$. Maximization implies $\Pi_S(0,u^*)>\Pi_S(0,u^{**})$ and we get $\Pi_S(y^{**},u^{**})>\Pi_S(0,u^{**})$ by implication. Using Proposition 2, we obtain $y^{**}>x^*(0,u^{**})$, i.e. a supplier R&D investment y^{**} does indeed lead to a corner solution in the buyer industry if condition (31) is satisfied.

$$(32)\quad \frac{\Pi_S(y^{**},u^{**})}{\Pi_S(0,u^*)} = \frac{k^{**}\cdot\delta^*}{k^*\cdot\delta^{**}} \left(\frac{c(u^{**},v)}{c(u^*,v)}\right)^{\frac{\varepsilon-1}{\varepsilon-(\alpha+\beta)(1-\varepsilon)}} \times$$

$$\times \left(\frac{\left(\frac{k^{**}}{\delta^{**}}\frac{\alpha(1-\varepsilon)}{\varepsilon-\beta(1-\varepsilon)}\right)}{\left(\frac{\alpha}{N}\right)}\right)^{\frac{\alpha(1-\varepsilon)}{\varepsilon-(\alpha+\beta)(1-\varepsilon)}} \left(1-\frac{\alpha(1-\varepsilon)}{\varepsilon-\beta(1-\varepsilon)}\right) > 1 \quad .$$

The right-hand side in (32) appears somewhat complex, but has clearly identifiable components. The first two terms reflect the differences in pricing due to the discontinuous change in the elasticity of factor demand. The third term captures two effects of upstream R&D. By providing $y>x^*(0,u)$, the supplier enhances downstream product quality, since the level of generic R&D employed by each firm is higher than in the case of a stand-alone industry. Furthermore, due to the complementarity between idiosyncratic and generic R&D, the supplier raises the productivity of downstream idiosyncratic R&D. These two effects enhance factor demand and increase upstream profits (gross of the cost of R&D). Finally, the last term in (32) reflects the supplier's cost of R&D.

A simplified *sufficient* condition can be derived by observing that - by definition of the maximization problem in (22) - $\Pi_S(y^{**},u^{**}) > \Pi_S(y^{**},u^*)$. It follows directly that

$$(33)\quad \Pi_S(y^{**},u^*) > \Pi_S(0,u^*) \Rightarrow \Pi_S(y^{**},u^{**}) > \Pi_S(0,u^*) \quad .$$

We obtain as a *sufficient* condition for the supplier to provide all of the generic R&D

$$(34)\quad \frac{\Pi_S(y^{**},u^*)}{\Pi_S(0,u^*)} = \left(\frac{N k^*}{\delta^*}\frac{(1-\varepsilon)}{\varepsilon-\beta(1-\varepsilon)}\right)^{\frac{\alpha(1-\varepsilon)}{\varepsilon-(\alpha+\beta)(1-\varepsilon)}} \times \left(1-\frac{\alpha(1-\varepsilon)}{\varepsilon-\beta(1-\varepsilon)}\right) > 1 \quad .$$

The sufficient condition (34) can be transformed into an inequality indicating a critical Herfindahl index for the downstream industry. Thus, generic R&D will be performed by the upstream monopolist supplier if

$$(35)\quad \frac{1}{N} < \left(\frac{k^*}{\delta^*}\frac{(1-\varepsilon)}{\varepsilon-\beta(1-\varepsilon)}\right) \times \left(\frac{\varepsilon-(\alpha+\beta)(1-\varepsilon)}{\varepsilon-\beta(1-\varepsilon)}\right)^{\frac{\varepsilon-(\alpha+\beta)(1-\varepsilon)}{\alpha(1-\varepsilon)}} \quad .$$

The interpretation of this inequality is straight-forward. With increasing N, the R&D incentives of downstream firms will suffer while the upstream supplier does not incur negative externalities form enhanced downstream competition. Ceteris paribus, a larger N will make supplier involvement in downstream product innovation more likely. Note, however, that N cannot be arbitrarily large due to the restriction (9) that firms have at least to break even in equilibrium. Nonetheless, parameter combinations which satisfy conditions (32) or (35) and condition (9) do exist. But the comparative statics with respect to most parameters of the model are not straight-forward. A discussion of the effects of various parameters is given in section 3.3 where several numerical examples for the basic model and some extensions are presented.

Another comment concerns the switching property of the equilibria described here. A small change in the underlying parameters, e.g. in the R&D elasticities, the production technology, or the demand elasticity can lead to a discontinuous switch from a regime in which the supplier is inactive (in terms of R&D) to one where the supplier contributes substantially to downstream product innovation. I noted before that this property of the model is consistent with several case studies that yielded a taxonomic distinction between distinct "technological regimes." While the explicit form of the solutions derived above depend on the convenient assumption that the supplier's R&D contribution is a perfect substitute for downstream generic R&D, one can obtain the switching property also with imperfect substitution between x and y.[22] However, in this case the supplier's R&D investment will never lead to a full crowding out of downstream generic R&D.

3. Extensions

This section briefly discusses two extensions of the model developed above. First, I will introduce intra-industry spillovers and relate them to the supplier's R&D incentives. Second, I will allow for an endogenously determined downstream industry structure and show that supplier R&D will reduce entry barriers at the downstream level and therefore lead to more vigorous competition.

In order to focus on the effects of supplier R&D, I will assume in subsections 3.1 and 3.2 that the price for the supplier's intermediate good u is given exogenously and constant at all levels of supplier R&D. This assumption also implies that the supplier's price-cost margin r (equivalent to its return on sales) and the supplier's share of downstream production cost k are constant.

[22] For example, one may specify product quality using the CES relationship $w(x,z;y)=z^{\beta}(x^{\phi}+y^{\phi})^{\alpha/\phi}$. Note that the previously used relationship (6) is nested within the CES specification (with $\phi=1$). The CES formulation does not allow for closed-form solutions, but with ϕ approaching unity the numerically obtained solutions for $x^*(y)$ get arbitrarily close to the R&D responses depicted in figure 1.

3.1 Intraindustry Spillovers

The model developed in the previous section is based on the assumption that generic R&D does not spill over from one firm to another, since firms in the downstream industry can protect their knowledge perfectly. Suppose now that R&D of the generic type is subject to *intraindustry spillovers*. In the presence of intra- *and* interindustry spillovers, product quality is now determined by the relationship

$$(36) \quad w_i(z_i,x_i;x_{-i},y) = z_i^{\beta}\Big(x_i + \theta\sum_{j\neq i} x_j + y\Big)^{\alpha} \qquad (0\leq\theta\leq1)$$

where x_{-i} indicates the vector of generic R&D expenditures made by the competitors of firm i. The exogenously given parameter θ in (36) denotes the degree to which a firm's generic R&D investment is subject to spillover effects. If $\theta=0$, then there are no spillover effects and the specification in (36) reduces to the case considered previously. Conversely, if $\theta=1$ then R&D results spill over fully to competing firms, and generic R&D becomes a public good in the downstream industry.

The analysis of the supplier's incentives to contribute to downstream quality improvements follows the logic of the previous section. It can be shown that - analogous to the previous situation without intraindustry spillovers - downstream firms will stop to invest in idiosyncratic R&D once the supplier's R&D investment y exceeds a critical level. Hence, there are no intraindustry spillovers then so that the results from the previous section do apply in full for this case.

It remains to analyze how intraindustry spillovers affect the results if the supplier does not crowd out downstream generic R&D with its own investment y. Clearly, the downstream firms' choices of quantity and of generic and idiosyncratic R&D are affected by intraindustry spillovers then. Let $q_\theta^*(y,u)$, $x_\theta^*(y,u)$, and $z_\theta^*(y,u)$ denote the respective equilibrium choices as a function of the supplier's R&D investment y and the exogenously given factor price u.

Using the same equilibrium notion as in the basic model, it is easy to show that the firms' generic and specific R&D investments in a symmetric equilibrium with intraindustry spillovers are given by

$$(37) \quad x_\theta^*(y,u) = [\sigma(1-\varepsilon/N)\, c(u,v)^{\varepsilon-1} (\alpha/N)^{\varepsilon} (\beta/\alpha)^{\beta(1-\varepsilon)}]^{1/[\varepsilon-(\alpha+\beta)(1-\varepsilon)]} \times$$

$$\times \Big(\frac{1}{1+\theta(N-1)}\Big) \Big(\frac{N-\varepsilon(1+\theta(N-1))}{N-\varepsilon}\Big)^{\frac{\varepsilon-\beta(1-\varepsilon)}{[\varepsilon-(\alpha+\beta)(1-\varepsilon)]}} - y \qquad \text{if } y<x_\theta^*(0,u)$$

and

(38) $z_\theta^*(y,u) = [\alpha(1-\varepsilon/N)\, c(u,v)^{\varepsilon-1} (\beta/N)^{\varepsilon} (\alpha/\beta)^{\alpha(1-\varepsilon)}]^{1/[\varepsilon-(\alpha+\beta)(1-\varepsilon)]} \times$

$$\times \left(\frac{N - \varepsilon(1 + \theta(N-1))}{N - \varepsilon}\right)^{\frac{\alpha(1-\varepsilon)}{[\varepsilon-(\alpha+\beta)(1-\varepsilon)]}} \qquad \text{if } y<x_\theta^*(0,u).$$

Since $\varepsilon>\beta(1-\varepsilon)$ by a previously made assumption[23], the equilibrium investment in generic R&D $x_\theta^*(y,u)$ is strictly decreasing in θ, the degree of intraindustry spillovers, no matter whether demand is elastic or inelastic. For the idiosyncratic R&D investment $z_\theta^*(y,u)$ we find that with elastic demand ($\varepsilon<1$), greater degrees of spillovers across firms tend to reduce z_θ^*, while they cause the opposite effect in the case of inelastic demand.

The downstream industry's total output $Q_\theta^*(y,u)$ can be calculated as

(39) $Q_\theta^*(y,u) = [\alpha(1-\varepsilon/N)\, c(u,v)^{(\alpha+\beta)(1-\varepsilon)-1} (\alpha/N)^{\alpha(1-\varepsilon)} (\beta/N)^{\beta(1-\varepsilon)}]^{1/[\varepsilon-(\alpha+\beta)(1-\varepsilon)]} \times$

$$\times \left(\frac{N - \varepsilon(1 + \theta(N-1))}{N - \varepsilon}\right)^{\frac{\alpha(1-\varepsilon)}{[\varepsilon-(\alpha+\beta)(1-\varepsilon)]}} \qquad \text{if } y<x_\theta^*(0,u).$$

The elasticity of demand determines whether spillovers have a positive or negative effect on industry output. As long as demand is elastic ($\varepsilon<1$), industry output is reduced since less R&D implies a reduction in product quality. In the case of inelastic demand, the model predicts a positive effect of spillovers on output.[24]

Naturally, these results are generalized versions of equations (14), (15), and (16) for the case of $y<x^*(0,u)$. Setting θ equal to zero leads us back to the model developed in section 2. The total R&D intensity of the downstream industry with intraindustry spillovers is given by

(40) $$\frac{x_\theta^*(.) + z_\theta^*(.)}{pq_\theta^*(.)} = \alpha\left(\frac{1}{1 + \theta(N-1)} - \frac{\varepsilon}{N}\right) + \beta\left(1 - \frac{\varepsilon}{N}\right) \qquad \text{if } y<x_\theta^*(0,u).$$

This expression is equivalent to the R&D intensity in the Levin and Reiss (1988) model. This is somewhat surprising, since their model is based on a different specification of a firm's product quality.[25]

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[23] Recall that I assumed $\varepsilon>(\alpha+\beta)(1-\varepsilon)$ in section 2 of the paper.

[24] With inelastic demand, decreasing product quality has a positive effect on output. In the presence of intraindustry spillovers, the quality indicator $w=z^\beta x^\alpha(1+\theta(N-1))^\alpha$ is decreasing in the degree of spillovers θ. Hence a positive effect on industry output.

[25] Levin and Reiss (1988) specify the quality indicator as $w_i = x_i^\beta (x_i + \theta\sum x_j)^\alpha$. The interpretation of the quality specification chosen in the model presented here is qualitatively similar to the one employed by Levin and Reiss. Nonetheless, the equality of the expressions for R&D intensity is slightly disturbing, since it demonstrates that different specifications of the underlying primitives may yield identical

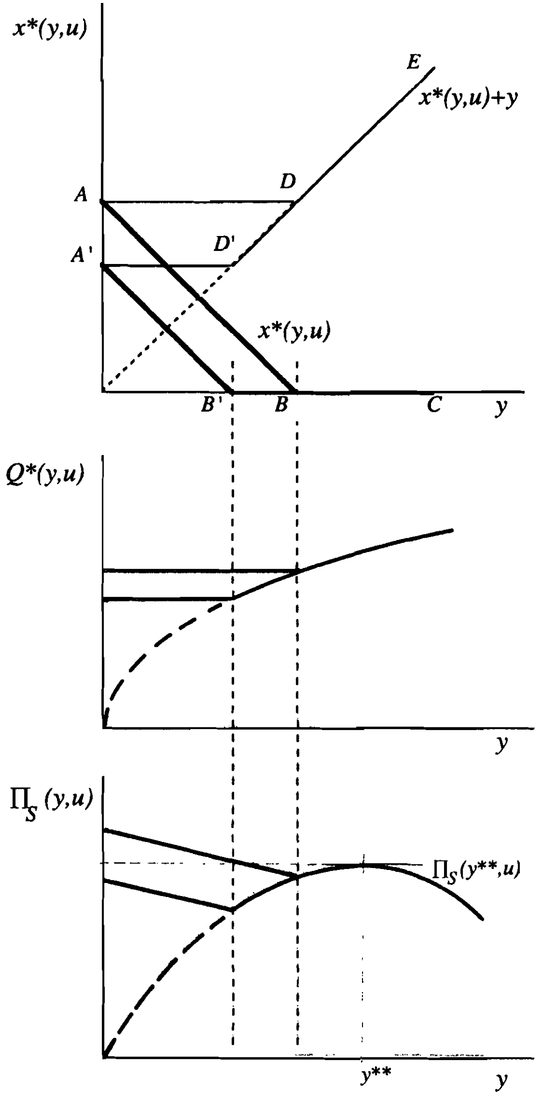

Figure 2
Supplier R&D Incentives in the Presence of Intraindustry Spillovers

results in terms of R&D intensity. Thus, while using R&D intensity as a variable in empirical studies helps to avoid numerous problems (e.g. accounting for R&D deflators (Griliches 1979) or different levels of production cost), it may well be subject to ambiguities in that researchers cannot be sure which model they are actually testing.

Intuitively, one would assume that the reduced downstream incentives will make upstream involvement more likely, since intraindustry spillovers reduce the downstream industry's output and hence the supplier's profit as long as $y<x_\theta^*(y,u)$. This can be shown in a formal argument replicating the steps from section 3, but I will instead present the graphical argument in figure 2.

Since the case of inelastic demand is not of interest here (see Proposition 1), the presence of spillovers unambiguously shifts the downstream firms' R&D investments to lower levels. In figure 2, the schedule ABC indicates a downstream firm's response in generic R&D $x^*(y,u)$, given that the supplier invests some amount y and that there are no spillovers. The schedule A'B'C represents the respective schedule $x_\theta^*(y,u)$ in the presence of spillovers (i.e. $\theta>0$), ceteris paribus. The transition point between the two regimes is shifted to the left-hand side.

The lower part of figure 2 depicts the supplier profit function for the two cases. Spillovers do not affect the supplier's profit function if downstream firms invest in idiosyncratic R&D only, since this type of R&D is not subject to spillovers. But the supplier's profit is reduced in the case of the interior downstream equilibrium, since downstream output contracts with increasing spillover rates if the supplier makes an R&D investment $y<x_\theta^*(0,u)$. The maximum supplier profit achievable without supplier R&D investment is reduced, while the maximum profit achievable with a supplier R&D investment y^{**} is not affected by downstream intraindustry spillovers.

In terms of the situation depicted in figure 2, the supplier will invest y=0 given the case that downstream generic R&D is not subject to spillovers. Conversely, in the presence of spillovers the profit level $\Pi_S(y^{**},u)$ clearly dominates the respective profit level $\Pi_S(0,u)$, hence the supplier will choose to invest $y=y^{**}$.

Evaluating the algebraic solutions, one can compute the analog to condition (35)

$$(41)\quad \frac{1}{N}\left(\frac{N-\varepsilon(1+\theta(N-1))}{N-\varepsilon}\right) < \left(r\,k\,\frac{(1-\varepsilon)}{\varepsilon-\beta(1-\varepsilon)}\right) \quad \left(\frac{\varepsilon-(\alpha+\beta)(1-\varepsilon)}{\varepsilon-\beta(1-\varepsilon)}\right)^{\frac{\varepsilon-(\alpha+\beta)(1-\varepsilon)}{\alpha(1-\varepsilon)}} .$$

The left-hand side of the inequality is strictly decreasing in the degree of intraindustry spillovers θ. Thus, according to this model, *a higher degree of intraindustry spillovers may cause either greater interindustry spillovers or, interpreting the supplier R&D effort as a quality enhancement of its intermediate products, greater quality of intermediate goods.* [26]

[26] Recent models of R&D spillovers have focused on the possibility that spillovers may actually encourage a firm's R&D efforts (e.g. Cohen and Levinthal 1989). Obviously, the relationship between inter- and intraindustry spillovers would be characterized by a negative correlation in this case. Clearly, this is an empirical problem, but to my knowledge an endogenous relationship between the two types of spillovers has not yet been discussed or investigated in the theoretical or empirical literature.

3.2 Endogenous Downstream Industry Structure

All of the above results relied on the assumption that the structure of the downstream industry is given exogenously. However, it can be shown that the incentives for supplier involvement in downstream quality improvements are even stronger if downstream industry structure is determined by the entry cost of R&D.

Qualitatively, the supplier's R&D investment serves an additional purpose in this case. By reducing the R&D investments of downstream firms, the supplier can reduce the barriers to entry and thus allow a comparatively greater number of firms to enter than would be sustainable without supplier investment in R&D. Greater competition among downstream firms has two effects. On the one hand, total industry output (and thus factor demand) will be greater the more firms enter the industry. On the other hand, more vigorous competition also reduces the downstream firm's R&D incentives.

A complete analysis of an endogenously determined industry structure in the presence of supplier R&D is relatively complex, since the simplifying properties of Proposition 2 can no longer be applied in this case. Even supplier R&D investments $y<x^*(0,u)$ will lead to a change in the supplier's profit, due to the effect of interindustry spillovers on downstream industry structure. This means that equilibria are theoretically possible in which both the supplier and downstream firms contribute to generic R&D. I will leave this possibility aside and focus on the two cases known from the above analysis.

In the following I will assume that the only entry costs incurred by downstream firms are those of R&D. Suppose first that the upstream supplier makes no R&D investment ($y=0$) so that we observe the equilibrium of a "stand-alone industry" where the free-entry number of firms is given by

(42) $n^* = \varepsilon/(\alpha+\beta)+\varepsilon.$

Now suppose that all generic R&D is accounted for by the supplier. Downstream firms invest in idiosyncratic R&D activities only. Then it is simple to show that the free-entry industry structure is characterized by a number of firms n^{**} where

(43) $n^{**} = \varepsilon/\beta+\varepsilon.$

To consider an extreme example, if the productivity of idiosyncratic R&D is zero ($\beta=0$) then the supplier's provision of generic R&D to downstream firms will yield a perfectly competitive buyer industry. Hence, the more productive downstream idiosyncratic R&D is, the more it will limit the supplier's power alleviate the vertical distortion.

It can be shown that the possibility of free entry into the downstream industry provides an additional incentive for the supplier to invest in R&D. Assume that condition (32) is satisfied, i.e. even with an exogenously given number of firms n* the supplier would invest y=y**. The supplier's profit is given by equation (30) in this case. Treating the number of firms N as a variable, one can differentiate the expression for the supplier's profit and find that $\Pi_S(.)$ is single-peaked and reaches a maximum with a downstream industry in which the number of firms is equal to

(44) $N_o=\varepsilon/\{(1-\varepsilon)\,\beta\}+\varepsilon.$

For the case of elastic demand and productive idiosyncratic R&D ($\beta>0$) one can easily show that

(45) $n^* < n^{**} < N_o$.

Hence, facing a downstream industry with n** firms is (ceteris paribus) more profitable for the supplier than facing an industry with n* firms.

Naturally, condition (32) is too strong now and by comparing the supplier's profit $\Pi_S(0)|_{N=n^*}$ (with zero R&D investment y and downstream industry structure n*) to the supplier's profit $\Pi_S(y^{**})|_{N=n^{**}}$ (with R&D investment y** and downstream industry structure n**) one can derive the necessary condition under which the supplier will again account for all generic R&D. The condition

(46) $$\Pi_S(y^{**})|_{N=n^{**}} > \Pi_S(0)|_{N=n^*}$$

can be transformed to

(47) $$\frac{\Pi_S(y^{**})|_{N=n^{**}}}{\Pi_S(0)|_{N=n^*}} = \left(\left(\frac{\beta}{1+\beta}\right)^{\beta(1-\varepsilon)} \left(\frac{1+\alpha+\beta}{\alpha+\beta}\right)^{1+(\alpha+\beta)(1-\varepsilon)} \right)^{1/[\varepsilon-(\alpha+\beta)(1-\varepsilon)]} \times$$

$$\times \left(k\, r\, \frac{\varepsilon\,(1-\varepsilon)}{\varepsilon-\beta(1-\varepsilon)} \right)^{\frac{\alpha(1-\varepsilon)}{\varepsilon-(\alpha+\beta)(1-\varepsilon)}} \left(1-\frac{\alpha(1-\varepsilon)}{\varepsilon-\beta(1-\varepsilon)}\right) > 1 \quad .$$

Again, the comparative statics are not trivial. However, one can show that for low R&D elasticities β, the profit ratio is increasing in α, the elasticity of R&D with respect to generic investments. Intuitively, if β is fairly small the supplier can - by facilitating entry into the industry - achieve a substantial reduction of the vertical distortion arising from downstream pricing above marginal cost . If α is small (relative to β, i.e. the difference between n* and n** is small), then the supplier's incentives to provide R&D results to the downstream industry approach the incentives in the case of an exogenously given industry structure.

It is worthwhile to explain in qualitative terms why the supplier prefers to see more competition in the downstream industry. An increase in the number of firms N has two effects on industry output. First, due to the externality from competition downstream firms will invest less in R&D and product quality in equilibrium is relatively smaller, thus causing the equilibrium level of output to fall. However, due to the direct effect of enhanced competition on quantity choices, the aggregate output of oligopolistic firms is also increasing in the number of firms. Given the assumptions of this model, the second effect dominates the first as long as the number of firms is smaller than N_0. The restriction to sustainable industry structures in condition (19) ensures that the latter condition is met and therefore the supplier's profit is unambiguously enhanced by further entry into the downstream industry.

3.3 A Numerical Example

Using the mathematical arguments above, one can show that greater factor cost shares k tend to enhance the supplier's R&D incentives. Similarly, the incentives become weaker as the the elasticity of substitution μ becomes larger, since the elasticity of factor demand increases with substitution opportunities.

The effects of other parameters are hard to determine due to the algebraic complexity of this model. The following numerical examples can provide some idea under what conditions supplier involvement in downstream product quality improvements is likely. Suppose that the downstream unit cost function is given by the Cobb-Douglas specification

$$(48) \quad c(u,v) = u^{\kappa} v^{1-\kappa} \ .$$

Choosing a Cobb-Douglas production function for the downstream industry is convenient here, since the cost shares are independent of factor prices in this case. The monopolist supplier's share of downstream production costs k is equal to κ, the parameter of the cost specification in (48). The elasticity of substitution implied by this specification is equal to one. Factor prices and cost levels in the downstream industry can thus readily be calculated.

In the following tabulations, I distinguish three basic cases. In the first case, the number of firms is given by n* (the free-entry structure), but does not change should the supplier decide to invest in R&D. Furthermore, there are no intraindustry spillovers in this case. The second case is equivalent to the first with the exception that generic R&D spills over completely across downstream firms (i.e. θ=1). Finally, in the third case there is free entry into the industry, i.e. the number of firms is equal to n* if the supplier does not invest in R&D, and it assumes the (higher) value of n** if the supplier provides the generic R&D results. All of the calculations underlying the results of Table 1 assume that factor prices are determined *endogenously.*

The parameters of interest are α and β, the elasticities of downstream product quality, and ε, the inverse of the elasticity of demand. Table 1 compares the profit ratio $\Pi_S(y^{**},u^{**})/\Pi_S(0,u^*)$ over a range of parameter combinations. In each of the three subtables, the elasticity of product quality with respect to idiosyncratic R&D β is held constant to facilitate comparisons. Cells with parameter combinations that do not result in supplier involvement are shaded in Table 1.

It is clear from section 3.1 that intraindustry spillovers favor supplier involvement in the case of an exogenously given industry structure. Similarly, comparing the case of an endogenously adjusting industry structure to one with a given number of firms, it is clear that the possibility of free entry enhances the profitability of upstream R&D. These expectations are borne out by the computations summarized in Table 1.

More interestingly, the tabulations demonstrate that greater opportunities for idiosyncratic R&D reduce the supplier's incentives to provide generic R&D to downstream firms: holding α and ε constant, greater values of β always imply a lower ratio $\Pi_S(y^{**},u^{**})/\Pi_S(0,u^*)$ in all of the three cases considered in Table 1. This result is not driven by the assumption that factor prices are determined endogenously here. Recall from equations (23) and (34) that the supplier's R&D investment lowers the elasticity of factor demand. This effect is the stronger the smaller the elasticity of product quality with respect to idiosyncratic R&D. Hence, higher values of β tend to reduce the pricing advantage that the supplier enjoys once generic R&D is no longer undertaken by downstream firms. But more detailed computations show that holding the elasticity of factor demand constant at the level given by equation (23) does not alter the result that greater values of β affect supplier incentives negatively, ceteris paribus.

Table 1 Profit Ratio $\frac{\Pi s(y^{**},u^{**})}{\Pi s(0,u^{*})}$

R&D Elasticities α	β	ε =.2 Case 1	ε =.2 Case 2	ε =.2 Case 3	ε =.4 Case 1	ε =.4 Case 2	ε =.4 Case 3	ε =.8 Case 1	ε =.8 Case 2	ε =.8 Case 3
0.01	0.01	1.042	1.051	1.067	1.018	1.026	1.034	1.001	1.005	1.012
0.02	0.01	1.051	1.070	1.119	1.025	1.041	1.061	1.001	1.009	1.023
0.03	0.01	1.040	1.068	1.161	1.025	1.048	1.084	0.999	1.011	1.033
0.04	0.01	1.014	1.050	1.195	1.020	1.051	1.105	0.996	1.012	1.042
0.05	0.01	0.975	1.018	1.223	1.011	1.050	1.122	0.993	1.013	1.051

R&D Elasticities α	β	ε =.2 Case 1	ε =.2 Case 2	ε =.2 Case 3	ε =.4 Case 1	ε =.4 Case 2	ε =.4 Case 3	ε =.8 Case 1	ε =.8 Case 2	ε =.8 Case 3
0.01	0.03	1.014	1.023	1.032	1.008	1.016	1.021	1.000	1.004	1.010
0.02	0.03	1.008	1.026	1.056	1.010	1.026	1.039	0.998	1.006	1.019
0.03	0.03	0.987	1.013	1.074	1.007	1.030	1.055	0.996	1.008	1.028
0.04	0.03	0.953	0.986	1.084	1.000	1.031	1.068	0.993	1.009	1.036
0.05	0.03	0.906	0.946	1.089	0.990	1.028	1.080	0.990	1.009	1.044

R&D Elasticities α	β	ε =.2 Case 1	ε =.2 Case 2	ε =.2 Case 3	ε =.4 Case 1	ε =.4 Case 2	ε =.4 Case 3	ε =.8 Case 1	ε =.8 Case 2	ε =.8 Case 3
0.01	0.05	0.996	1.005	1.013	1.003	1.010	1.014	0.999	1.003	1.009
0.02	0.05	0.978	0.995	1.020	1.001	1.016	1.027	0.997	1.004	1.017
0.03	0.05	0.945	0.970	1.021	0.995	1.017	1.038	0.994	1.006	1.024
0.04	0.05	0.900	0.931	1.015	0.986	1.015	1.047	0.991	1.006	1.032
0.05	0.05	0.843	0.880	1.002	0.974	1.010	1.055	0.987	1.007	1.039

Case 1: exogenously given industry structure ($N=n^*$), no intraindustry spillovers in generic R&D
Case 2: exogenously given industry structure ($N=n^*$), complete intraindustry spillovers in generic R&D
Case 3: endogenously given industry structure, no intraindustry spillovers in generic R&D

Common Parameters: $\mu=1$ (Cobb-Douglas Cost Function), $k^*=.5$

4. Concluding Remarks

This model demonstrates that industry outsiders (e.g. a supplier) may have R&D incentives that dominate those of the producers of the respective good. The supplier's R&D incentives discussed in this model are of a strategic nature, since the returns to the investment are appropriated in an indirect way via enhanced factor demand. The consequences of the outsider's investment can be striking. While downstream product quality is enhanced, the R&D intensity of the industry is reduced once the supplier engages in R&D. Furthermore, though the exogenously defined relationship between product quality and R&D investment allows for two kinds of downstream R&D efforts, the upstream involvement in R&D effectively limits the "technological opportunities" of the downstream producers.

The supplier's transfer of R&D results can take the form of intentionally generated interindustry spillovers. This notion contradicts the conventional interpretation that spillovers are essentially a regrettable, but unavoidable byproduct of research and development. The production of spillovers can be profitable if they convey - via some externality - a beneficial effect on the originator of the spillover information. In the model presented here such a mechanism exists, since the monopolist supplier can capture demand spillovers caused by downstream improvements of product quality. In addition, the model leads to the conclusion that intra- and interindustry spillovers may be related phenomena.

An important conclusion is that one cannot interpret a comparatively low R&D intensity of a given industry as an indicator of an insufficient degree of technical progress. Firms in the respective industry may simply take advantage of R&D results that are provided by outsiders out of strategic motivations. This result may explain why the estimation of models that did not account for vertical interaction explicitly has produced unrealistically low R&D elasticities for some industries. For example, Levin and Reiss (1988, p.554) comment that their estimates of R&D elasticities appear to be too low in the case of the plastics products industries. Interestingly, the available evidence from case studies (Corey 1956) suggests indeed that plastics materials producers have engaged in considerable R&D efforts to provide process and product design know-how to their buyers. Hence, the model presented here may provide a tentative explanation for surprising estimation results like the one obtained by Levin and Reiss.

The model has particularly important implications for cross-sectional and longitudinal empirical work that attempts to study the determinants of R&D and innovation. It seems clear that econometric models at the industry or firm level should include variables that measure the R&D contributions that firms in a given sector receive from other industries or institutions like government laboratories and universities. However, treating such observed contributions as exogenous measures in a regression framework may lead to biased estimation results. Some care has to be taken to specify the underlying processes that determine the extent of outside R&D contributions.

The functional forms used in empirical work are of some concern, too. The model developed here supports the notion of distinct "technological regimes," one in which the supplier contributes significantly to downstream innovation and one in which all R&D is done by downstream oligopolists. A transition between these regimes can be discontinuous, as it is the case in this model. The correct approach to estimation would then involve a switching regression framework in which the transition between the two (or more) regimes is determined endogenously. To my knowledge such an approach has not yet been used in empirical work on R&D.

While the above model has focused on quality-enhancing R&D in the downstream production process, a similar model can be devised with regard to process innovations (Harhoff 1991a). Moreover, the mechanism of appropriating returns to R&D via strategically induced demand growth can be applied to a variety of settings. The operating principle is simply that one sector can capture demand (or other) spillovers induced by cost reduction or product improvement in another sector. While not modelled here, one can apply this basic principle easily to industries with demand complementarities or to monopsonistic players who may seek to induce price reductions among their suppliers.

Furthermore, the idea can be applied to other types of intangible firm investments like advertising. Mathewson and Winter (1984) have pointed out that intra-industry advertising spillovers may cause underinvestment at the retailer level which can be corrected by upstream involvement in advertising. The model developed here suggests that advertising at the supplier level may serve another purpose. The supplier may attempt to prevent downstream firms from establishing many different brands which lead to enhanced sunk cost expenditures and a reduction of the number of downstream competitors.[27]

Further research could progress in several directions from this point. Some of the implications developed here need to be tested empirically. Also, the robustness of the results presented here should be scrutinized, since they depend on assumptions regarding the functional form of demand and quality relationships. Finally, models other than this non-tournament example should be used to test whether industry outsiders may have significant incentives to manipulate the industry's "stand-alone" equilibrium.

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[27] There appear to be recent instances of such strategies. For example, DuPont is a supplier of fibers for carpets that can be cleaned easily. These carpets are advertised under the DuPont brand name "Stainmaster" and DuPont has financed its advertisement on national television and in other media.

References

Acs, Z. J. and D. B. Audretsch (1987). "Innovation, Market Structure, and Firm Size," Review of Economics and Statistics. Vol. 69, pp. 567-574.

Acs, Z. J. and D. B. Audretsch (1988). "Innovation in Large and Small Firms: An Empirical Analysis," American Economic Review. Vol. 78, pp. 678-690.

Allen, R. G. B. (1938). Mathematical Analysis for Economists. London, Macmillan.

Arrow, K. J. (1962). "Economic Welfare and the Allocation of Resources for Invention," in: R. R. Nelson (Ed.). The Rate and Direction of Inventive Activity: Economic and Social Factors, pp. 609-626. Princeton, Princeton University Press.

Bernstein, J. I. (1988). "Costs of Production, Intra- and Interindustry R&D Spillovers: Canadian Evidence," Canadian Journal of Economics. Vol. 21, pp. 324-347.

Bernstein, J. I. and M. I. Nadiri (1988). "Interindustry R&D Spillovers, Rates of Return, and Production in High-Tech Industries," AEA Papers and Proceedings. Vol. 78, pp. 429-434.

Binswanger, H. P. and V. W. Ruttan (1978). Induced Innovation - Technology, Institutions, and Development. Baltimore, Johns Hopkins University Press.

Bradburd, R. M. (1982). "Price-Cost Margins in Producer Goods Industries and the Importance of Being Unimportant," Review of Economics and Statistics. Vol. 69, pp. 575-583.

Bronfenbrenner, M. (1961). "Notes on the Elasticity of Derived Demand," Oxford Economic Papers. Vol. 13, pp. 254-261.

Caves, R. E., H. Crookell and J. P. Killing (1983). "The Imperfect Market for Technology Licenses," Oxford Bulletin of Economics and Statistics. Vol. 45, pp. 223-248.

Cohen, W. M. and R. C. Levin (1989). "Empirical Studies of Innovation and Market Structure," in: R. Schmalensee and R. D. Willig (Ed.). Handbook of Industrial Organization, Vol. 2, pp. 1060-1107. Amsterdam, North-Holland.

Cohen, W. M. and D. A. Levinthal (1989). "Innovation and Learning: The Two Faces of R&D," Economic Journal. Vol. 99, pp. 569-596.

Corey, E. R. (1956). The Development of Markets for New Materials. Boston, Division of Research, Graduate School of Business Administration, Harvard University.

Dasgupta, P. and J. Stiglitz (1980). "Industrial Structure and the Nature of Innovative Activity," Economic Journal. Vol. 90, pp. 266-293.

Dixit, A. (1979). "Quality and Quantity Competition," Review of Economics and Statistics. Vol. 46, pp. 587-599.

Graham, M. B. W. and B. H. Pruitt (1990). R&D for Industry - A Century of Technical Innovation at Alcoa. Cambridge, Cambridge University Press.

Griliches, Z. (1979). "Issues in Assessing the Contribution of Research and Development to Productivity Growth," Bell Journal of Economics. Vol. 10, pp. 92-116.

Harhoff, D. (1991a). "Innovation, Oligopoly, and Derived Demand." mimeo, Zentrum für Europäische Wirtschaftsforschung (ZEW), Mannheim.

Harhoff, D. (1991b). Vertical Organization, R&D Incentives and Strategic Spillover Production. Unpublished Ph.D. Thesis. Cambridge, Mass.: Massachusetts Institute of Technology.

Jaffe, A. B. (1986). "Technological Opportunity and Spillovers of R&D: Evidence from Firms' Patents, Profits, and Market Value," American Economic Review. Vol. 76, pp. 984-1001.

Koenker, R. W. and M. K. Perry (1981). "Product Differentiation, Monopolistic Competition, and Public Policy," Bell Journal of Economics. Vol. 12, pp. 217-231.

Kogut, B. and U. Zander (1989). "Knowledge of the Firm and the International Replication of Technology." Working Paper, Wharton School, Philadelphia.

Lee, T. K. and L. L. Wilde (1980). "Market Structure and Innovation: A Reformulation," Quarterly Journal of Economics. Vol. 94, pp. 429-436.

Leenders, M. R. and D. L. Blenkhorn (1988). Reverse Marketing - The New Buyer-Supplier Relationship. New York, Free Press.

Levin, R. C., W. M. Cohen and D. C. Mowery (1985). "R&D Appropriability, Opportunity, and Market Structure: New Evidence on Some Schumpeterian Hypotheses," AEA Papers and Proceedings. Vol. 75, pp. 20-24.

Levin, R. C. and P. C. Reiss (1988). "Cost-Reducing and Demand-Creating R&D with Spillovers," Rand Journal of Economics. Vol. 19, pp. 538-556.

Levin, R. C. and P. M. Reiss (1984). "Tests of a Schumpeterian Model of R&D and Market Structure," in: Z. Griliches (Ed.). R&D, Patents, and Productivity, pp. 175-208. Chicago, University of Chicago Press.

Loury, G. C. (1979). "Market Structure and Innovation," Quarterly Journal of Economics. Vol. 43, pp. 395-410.

Mathewson, G. F. and R. A. Winter (1984). "A Economic Theory of Vertical Restraints," Rand Journal of Economics. Vol. 15, pp. 27-38.

Mishina, K. (1989). Essays on Technological Evolution. Unpublished Ph.D. Thesis. Cambridge, Mass.: Harvard University.

Nelson, R. R. (1980). "Production Sets, Technological Knowledge, and R&D: Fragile and Overworked Constructs for Analysis of Productivity Growth?," AEA Papers and Proceedings. Vol. 70, pp. 62-67.

Nelson, R. R. (1982). "The Role of Knowledge in R&D Efficiency," Quarterly Journal of Economics. Vol. 97, pp. 453-470.

Pavitt, K. (1984). "Patterns of Technical Change: Towards a Taxonomy and a Theory," Research Policy. Vol. 13, pp. 343-373.

Peck, M. J. (1962). "Inventions in the Postwar American Aluminum Industry," in: The Rate and Direction of Inventive Activity: Economic and Social Factors, pp. 279-298. Princeton, N. J., Princeton University Press.

Polanyi, M. (1958). Personal Knowledge: Towards a Post-Critical Philosophy. Chicago, University of Chicago Press.

Rosenberg, N. (1982). Inside the Black Box - Technology and Economics. Cambridge, Cambridge University Press.

Sato, R. and T. Koizumi (1970). "Substitutability, Complementarity, and the Theory of Derived Demand," Review of Economic Studies. Vol. 39, pp. 107-118.

Spence, M. A. (1984). "Cost Reduction, Competition, and Industry Performance," Econometrica. Vol. 52, pp. 101-121.

Tandon, P. (1983). "Rivalry and Excessive Allocation of Resources to Research," Bell Journal of Economics. Vol. 14, pp. 152-165.
Tandon, P. (1984). "Innovation, Market Structure, and Welfare," American Economic Review. Vol. 74, pp. 394-403.
Teece, D. J. (1977). "Technology Transfer by Multinational Firms: The Resource Cost of Transferring Technological Know-How," Economic Journal. Vol. 87, pp. 242-261.
Tirole, J. (1988). The Theory of Industrial Organization. Cambridge, Mass., MIT Press.
VanderWerf, P. A. (1990). "Modelling Process Innovations by Materials Suppliers as a Function of Expected Innovation Rents." Working Paper, Boston University, School of Management, Boston, Mass.
Varian, H. R. (1984). Microeconomic Analysis. New York, Norton.
von Hippel, E. (1982). "Appropriability of Innovation Benefit as a Predictor of the Source of Innovation," Research Policy. Vol. 11, pp. 95-115.
von Hippel, E. (1988). The Sources of Innovation. New York, Oxford University Press.
von Hippel, E. (1990). "The Impact of "Sticky Data" on Innovation and Problem-Solving." Working Paper No. 3147-90 BPS, Alfred P. Sloan School of Management, Massachusetts Institute of Technology, Cambridge, Mass.
Waterson, M. (1980). "Oligopoly and Derived Demand," Economics Letters. Vol. 5, pp. 115-118.
Winter, S. G. (1984). "Schumpeterian Competition in Alternative Technological Regimes," Journal of Economic Behavior and Organization. Vol. 5, pp. 287-320.