STRATEGIC SPILLOVER PRODUCTION, VERTICAL ORGANIZATION, AND INCENTIVES FOR RESEARCH AND DEVELOPMENT

by

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Abstract

This thesis studies circumstances under which firms intentionally engage in the production of spillover information. I propose a concept of strategic appropriation that involves i) the intentional production of spillover information for use by firms in vertically related sectors and ii) the capturing of externality benefits caused by the intentional dissemination of the information.

The thesis focuses on strategic incentives of supplier firms to provide a downstream sector with spillover information. The suppliers' intentional provision of spillovers may accommodate entry into the downstream industry, enhance the downstream industry's productivity, or prevent the emergence of downstream market power, e.g. in the form of a downstream patent monopoly. Suppliers can appropriate a return to their strategic R&D investments through enhanced factor demand.

The thesis analyzes several implications of the strategic appropriation concept. First, R&D incentives and industry structure can be manipulated by firms in vertically related sectors. Second, strategic appropriation creates additional R&D incentives for the spillover producer, even if the market for information fails completely. Third, the vertical organization of production activities may become an important determinant of information flows and R&D incentives.

Modelling these strategic supplier incentives suggests that intentional spillover production is likely to occur under specific conditions within a vertical channel of production activities. Supplier firms will tend to provide more information the smaller the free-rider effect in the upstream industry, the greater their return on increased factor sales, and the more fragmented the downstream industry. Downstream R&D intensity should be reduced under these conditions. This prediction is confirmed in a cross-sectional regression analysis, using data on industry R&D intensity, supply sector structure, and industry-specific technology and demand conditions.

THESIS SUPERVISOR:	Eric von Hippel
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Contents

Chapter I

Chapter II

Chapter III

Chapter IV

Chapter V

Chapter VI

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This thesis is dedicated to my parents.

Chapter I
Introduction

I.1 Introduction

Case studies in the marketing and industrial purchasing literatures have repeatedly pointed out that firms sometimes choose to "give away" privately generated R&D knowledge without being able or wanting to charge a licensing fee or sales price in return. For example, much of the research and development efforts to develop materials processing techniques are often performed by the producers of these materials and then made available to manufacturers of final goods. These observations were first laid out in early work by Raymond E. Corey (1956) and reemerged in a series of studies by other authors (Graham and Pruitt 1990; Leenders and Blenkhorn 1988; Peck 1962; VanderWerf 1990a; VanderWerf 1990b; von Hippel 1988a).

This form of firm behavior is striking, since it suggests that these firms must be able to appropriate a return on their R&D investment in an indirect way, i.e. without selling their embodied or non-embodied technological knowledge. Moreover, the voluntary production of knowledge that is spilled over to other sectors contradicts the widely held view that spillovers occur only involuntarily, since firms cannot prevent the leaking of information.

I suggest in this thesis that this type of R&D investment can be explained as a "strategic appropriation" phenomenon.[1] I hypothesize that firms can appropriate a return to R&D by i) providing to firms in a related industry some technological knowledge as a public good, and ii) capturing a return from an externality effect caused by the dissemination of this knowledge.[2] Appropriating a return on the R&D investment is in this case not based on the sales of technological knowledge in embodied or disembodied form, but on capturing externality benefits caused by the strategic R&D investments.

Such a mechanism is of theoretical and practical interest for three main reasons. First, its existence may affect the overall R&D investment that firms are willing to make. Given that our understanding of R&D incentives is still limited[3], an investigation of strategically motivated R&D may then shed more light on the composition and extent of a firm's R&D activities. Second, strategic appropriation involves the intentional production of spillovers. As I will demonstrate in my literature survey, much of the recent spillover discussion is based on the assumption that spillovers are an unavoidable consequence of information production. The possibility of intentional spillover production renders this conventional view imprecise at best, and seriously incomplete at worst. Third, the concept of strategic appropriation raises interesting issues regarding the relationship between R&D incentives and vertical organization. I argue below that vertical interdependencies between industries provide the externality mechanism that helps firms to reap a return on the strategic production of public goods knowledge. For example, a monopolist supplier may be able to profitably provide downstream firms with cost-reducing information while competitive suppliers are precluded from the use of strategic appropriation. In the case of the monopolist supplier, downstream cost reduction causes a positive demand externality, while competitive suppliers (producing at marginal cost) are indifferent with respect to enhanced demand.

These elements are drawn together in this thesis in a theoretical and empirical analysis of incentives for strategic R&D investments. The following section provides a brief description of the structure of this thesis, and of the main points made in each of the chapters.

I.2 Structure of the Thesis

As I pointed out, a novel element of this work is that interindustry information spillovers are treated as choice variables. In order to relate this view to the conventional perspective on information spillovers, I dedicate chapter II to summarizing the respective literature in a critical way. Chapter II also includes a more detailed discussion of the case study literature that motivated my initial interest in this topic.

In chapter III, I present a formal two-sector model of process innovation. A monopolist supplier faces a downstream industry in which firms can reduce their production cost by investing in R&D efforts. Entry into the downstream industry is only limited by the requirement that firms have to break even, i.e. profits are just sufficiently high to cover the sunk cost of R&D expenditures. The model focuses on the supplier's incentives to provide downstream firms with public goods information which serves as a substitute for private R&D efforts. I show that this form of knowledge production leads to an increase in the number of firms sustainable in the downstream industry. The supplier may profit from this effect since greater competition implies enhanced upstream profits. Implications for welfare and measurement of R&D intensity are also developed in chapter III.

In chapter IV, I demonstrate that the monopolistic supplier may want to promote the extent or speed of downstream innovation, or preempt downstream innovators who seek to patent their technology. By preempting downstream innovation, the ex ante structure of the industry can be maintained. Obviously, this strategy is then particularly rewarding if the transition from a competitive to a monopolistic downstream sector can be prevented, i.e if the ex ante industry structure is perfectly competitive.

Chapter V derives testable hypotheses that are consistent with these theoretical results. These hypotheses are tested in a cross-section of industries. I also explore the effect of vertical organization on an industry's patenting propensity, based on the hypothesis that dependence on "strong" suppliers will induce firms to seek stronger patent protection for their technologies.

Finally, in the concluding chapter VI, I summarize the theoretical and empirical results, discuss their implications, and suggest directions for future research.

In the remainder of this initial chapter, I want to address four points. First, in section I.3, I will discuss in more detail the concept of strategic appropriation, since it is of central importance for this work. Second, in section I.4, I will discuss the scope of its applicability. Specifically, I will describe three types of industrial settings that give rise to strategic appropriation incentives. Third, in section I.5, I will describe three particular mechanisms of strategic appropriation. I suggest that firms may make strategic R&D investments in order to accommodate entry, promote innovation, or prevent the emergence of market power in vertically related sectors. Finally, in section I.6, I will describe the contribution of this work to the literature.

I.3 The Concept of Strategic Appropriation

Contributions to the strategy and 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."[4] 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 with respect to their R&D intensity and use industry-specific measures as independent variables (Cohen and Levin 1989). While intraindustry effects are emphasized by this methodological approach, the importance of interindustry relationships is often neglected.

The focus on one-sector models in the R&D literature has led many researchers to consider only a limited range of alternative appropriation mechanisms. The classical view in the innovation literature is that firms can appropriate returns from R&D either through in-house use of their technological knowledge (i.e. as product and process innovations) or by trading the knowledge itself.

In the case of in-house use of R&D results the technological innovation reaches the market in output-embodied form (von Hippel 1982). How efficient these appropriation mechanisms are depends on a number of factors, such as the strength of legal protection mechanisms (patents and copyrights), the innovator's capability to protect the innovation as a trade secret, and the lead time and related first-mover advantages that an innovator can achieve in the market. These factors are assumed to differ substantially across industries and technologies (Cohen and Levin 1989; Levin, Klevorick et al. 1987).

The second appropriation mechanism relies on the licensing or exchange of non-embodied knowledge. The theoretical literature on licensing has analyzed in depth the characteristics of optimal licensing contracts (Gallini and Wright 1990; Katz and Shapiro 1985; Shapiro 1985). However, empirical evidence seems to suggest that real-world licensing contracts fall far short of the first-best solution. Caves, Crookell, and Killing (1983) find that an innovator can expect to appropriate only a small fraction of the innovation's value through licensing. Firestone (1971) finds that most patents are never licensed and that patents owned by independent inventors are usually licensed to one firm only. Further support for the view that licensing is often rather ineffective is summarized by Levin et al. (1987) and von Hippel (1988a).

These two alternatives for appropriating returns to R&D (embodiment of knowledge in process and product innovations, and licensing or exchange of disembodied knowledge) can be considered direct appropriation mechanisms since the innovator obtains its return on innovation efforts in an exchange relationship.[5]

In this thesis I want to analyze an additional appropriation mechanism that does not rely on direct exchange. I will refer to this mechanism as indirect or <u>strategic appropriation</u>. Strategic appropriation consists of i) providing to other firms some technological knowledge as a public good, and ii) capturing a return from the externality effect caused by the dissemination of this knowledge. Appropriation is indirect here because the innovator will neither use the generated technological knowledge in-house, nor will the technology be licensed. Appropriation relies (in the pure case) completely on the effects that are caused by the innovator's R&D investment in other industries, e.g. changes in costs and product quality, rate of entry, extent of competition, or speed of technology adoption. These effects then benefit the innovator indirectly via growing demand for its own product or via reductions in input prices.

Strategic appropriation is essentially an exchange of externality benefits. The innovator provides its R&D results as a public good and enjoys in turn a portion of the externality benefits caused by its investment. As I will show below, strategic appropriation is particularly efficient if the innovator commands a relatively large market share, since a larger share of the externality benefits induced by the knowledge production and dissemination can be captured then.[6]

I.4 Applicability of Strategic Appropriation

The benefits from innovation are often fragmented so that several agents receive benefits from and have an interest in innovation of a particular kind. In a world where externalities cause major economic imperfections, the actual producer of a good or service may not be the agent with the greatest incentives to pay for the development of product improvements or cost-reducing technologies. R&D and production may then be undertaken by two different enterprises although R&D results cannot be traded.

Direct compensation for R&D efforts is replaced in the strategic appropriation mechanism by an externality benefit caused by the dissemination of knowledge. I argue that this concept is particularly relevant when applied to a system of vertically related industries. Firms in vertically related production activities are often tied to each other by virtue of strong interindustry externalities. For example, a reduction of production costs in one industry may cause an increase in profits in another sector. Similarly, greater product quality in one industry may lead to enhanced demand for a good, and therefore generate enhanced factor demand for input suppliers.

Vertical externalities arise necessarily if at least one sector in a vertical chain of production activities deviates from the ideal of a perfectly competitive industry. Modern oligopoly theory has provided many rationales that can account for such imperfections. The resulting externalities are the reason why we can often observe adversarial relationships among vertically related firms.[7] Firms in different sectors are engaged in vertical competition for a beneficial distribution of the rents created in a chain of production activities. The allocation of these rents depends greatly on the extent of competition and innovation in all sectors of the channel. This problem has been discussed extensively in the vertical restraint literature[8], but its implications for technical change and innovation incentives have been largely neglected.

To demonstrate the wide applicability of strategic appropriation, I provide here a description of three particular types of vertical interdependence that can give rise to strategic appropriation incentives.

Consider first a monopolist who sells a commodity to firms in a downstream industry. This structure is similar to the classical manufacturer-retailer configuration in the vertical restraint literature. A greater extent of innovation and a greater degree of competition in the downstream industry are often advantageous for the supplier. Greater competition in the buyer industry will lower market prices for the final good and - if demand is elastic - will lead to greater industry output. In all likelihood, this will also imply greater factor demand and greater profits for the supplier. Similarly, if downstream firms engage in cost-reduction efforts or product improvements, then such investments are likely to enhance upstream rents along a similar causal chain. Factors that reduce competition or the extent of innovation are likely to reduce the supplier's profits.[9] The supplier may therefore have incentives to manipulate both the extent of innovation and the degree of competition in the downstream industry.

An upstream monopoly is not a necessary condition for strategic appropriation to occur, but greater monopoly power in the supply sector will strengthen the strategic incentives. If a few firms "own" an industry, then they are likely to be more concerned about the overall size of the pie than perfectly competitive firms would be. If changing the vertical rent distribution is a public good for all suppliers of a commodity, then active involvement in the strategies considered below is most likely if few firms share the returns. Free-rider problems will otherwise discourage the strategic investments.

Very similar considerations can be applied to the second setting. Consider a monopsonist who receives some factor of production from a set of competitive suppliers. Ceteris paribus, the monopsonist will be interested to procure its inputs at the lowest possible cost level. Again, both the pattern of innovation and the extent of competition in the vertically related sector are of interest to the downstream firm.

Complementary goods relationships provide the third class of interdependencies. I classify these relationships here as "vertical", since they are - from an economic point of view - very similar to the standard buyer-supplier relationship (Tirole 1988). Structurally similar incentives also create similar behavioral patterns: one can often observe the same mixture of cooperative and adversarial elements in complementary goods relationships that is familiar from buyer-supplier interactions. The interdependence between producers of computer hardware and firms in the software industry is a particularly interesting example.[10]

In all of these cases, firms in the monopolistically (or oligopolistically) organized sector may experience incentives to influence innovation and competition in the vertically related industry. To facilitate the discussion in the following sections, I will focus on one type of vertical interdependence only and analyze the motives of a monopolistic supplier who seeks to manipulate the patterns of innovation and competition in a downstream buyer industry. The following section provides a description of three specific strategic mechanisms that the supplier firm can employ.

I.5 Mechanisms of Strategic Appropriation

In this section I provide the reader with a short overview of three basic strategic appropriation mechanisms. These are discussed in greater detail in chapters III and IV of the thesis.

I.5.1 Promoting Downstream Innovation

A supplier firm may find that its customers lack sufficient incentives to undertake cost reducing or quality-improving innovations. Suppose there is one monopolistic supplier whose profits are increasing with the total output of the downstream industry. Lower downstream production costs would presumably lead to lower prices, greater sales and finally greater demand for the supplier's intermediate good. Improved quality of downstream products may have very similar effects.

The lack of sufficiently strong innovation incentives in the downstream industry may be due to several reasons. The existence of a concentrated supply sector may in itself reduce downstream bargaining power and appropriability (Williamson 1975), but this effect is only one among many possibilities. Weaknesses in the downstream appropriability regime can also be due to the nature of legal protection mechanisms. Furthermore, small downstream enterprises may be risk-averse and less likely to undertake R&D investments if the technological or commercial success of research projects is highly uncertain. Large suppliers may be in a better position to insure against the technological and economic risk.

To provide a clear case, assume that all technological knowledge generated by private R&D efforts spills over completely to competing downstream firms and that contracts governing the sale or licensing of this knowledge are infeasible. Despite the fact that all R&D is a public good firms may still want to invest to some degree since they can capture a small portion of the total benefits generated by their R&D effort (Rosenberg 1990). But the greater the number of firms operating in the industry, the lower will be each firm's R&D investment (Spence 1984). The supplier does not face a disincentive effect from spillovers, since it appropriates the aggregated returns from downstream output expansion. The upstream firm then has an incentive to develop innovations and spill them over to the downstream firms.

The picture changes if the supplier itself operates in an oligopolistic industry. Maintaining the assumption that upstream firms produce a commodity, there will now be a free-rider effect among supplier firms. Downstream buyers will have the possibility to procure their commodity input with any of the suppliers and still utilize the spillover information provided by the innovating supplier. But we should expect to see upstream involvement in downstream innovation as long as the number of suppliers is small in comparison to the number of buyers, and as long as the supply industry receives relatively large returns on downstream cost reductions or product improvements. The latter condition is equivalent to requiring a high price-cost margin for the suppliers and a high cost share of the suppliers' intermediate product in the downstream production process.

The supplier's incentives are also affected by the structure of the downstream industry. A graphical illustration of this effect is sketched in Figure I.1. Assume that an upstream supplier can acquire a cost-reducing technology at some cost and transfer it to downstream firms. Furthermore, let the upstream firm's profit be an increasing function of downstream output as one could reasonably expect. The innovation reduces downstream costs from the ex ante level c to the ex post level c' so that $\Delta c = c - c'$. Consider first the case of a downstream monopoly. The downstream monopolist will be able to restrict ex post output and the cost reduction will translate into a relatively small increase in output ΔQ_M. Conversely, in the case of a perfectly competitive downstream industry that adopts the supplier's technology, there will be no restriction on ex post industry output and the supplier enjoys the greatest possible increase in factor demand, denoted ΔQ_C in Figure I.1. Upstream incentives to induce a cost reduction effect will then be the stronger the closer the downstream industry approaches the competitive ideal. A completely analogous argument can be made in the case of a product innovation.

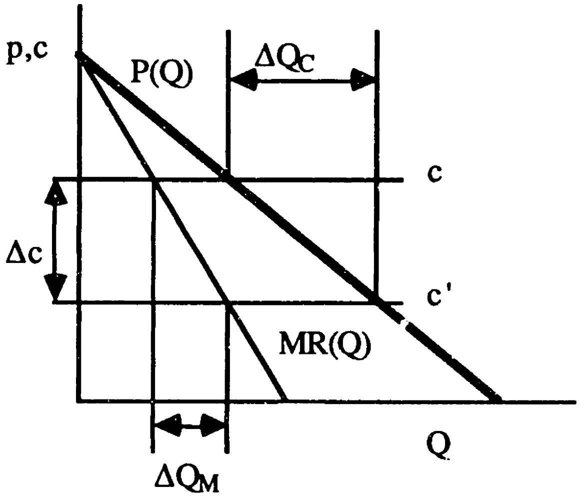

Figure I.1
Output Effect of a Cost-Reducing Innovation

This loosely stated argument reveals an interesting redundancy property of market economies. It is often alleged that weak R&D incentives in any given sector of the economy imply that comparatively little innovation will occur. However, supplier firms may be sufficiently interested to promote innovation in that sector. The redundancy mechanism would not work if the economy were organized in a completely competitive way, since there are no externalities across vertically related sectors in such a scenario.

I.5.2 Accommodating Entry

Even if a supplier may judge the innovation efforts undertaken by its customers to be sufficiently high, the downstream firms may cause losses to the upstream sector by colluding in their price policy or by erecting barriers to entry which help to maintain high oligopolistic prices. The supplier will have to share the total surplus in the production chain with downstream firms if these can or have to maintain a price level above marginal costs. Downstream R&D itself may represent a barrier to entry and require pricing above marginal costs if R&D expenditures have sunk cost properties (Dasgupta and Stiglitz 1980).

The upstream firm may then seek to encourage new entrants to come in and induce downstream price reductions. The supplier invests in this case in order to have control over the conditions for downstream entry. Conversely, the buyer firms have an interest to withhold such knowledge from new entrants and from the supplier firms. It is important to note that accommodating entry into the downstream industry may lead to deterioration of downstream innovation incentives since the marginal return to R&D is likely to decrease in the number of competitors.[11] The supplier's R&D investment then also serves to compensate possible disincentive effects resulting from greater competition in the buyer industry. In essence, the supplier chooses a trade-off between downstream competition and downstream innovation incentives that yields the highest upstream profits.

Note also that downstream entry - like promotion of downstream innovation - is a public good for suppliers producing a commodity. The strategic incentives are then particularly strong then if the supply industry is organized monopolistically or in the hands of very few firms.

I.5.3 Preventing the Emergence of Market Power

Incentives for supplier involvement in downstream innovation may arise even if the downstream sector is perfectly competitive ex ante. Consider the possibility that one of the downstream firms obtains a patent on some technology and that it monopolizes the downstream industry. Firms in the supply sector could conceivably profit from such a development if it is accompanied by a downstream output expansion, but they would prefer to have control over the technology and make it available to all downstream producers. Preempting downstream innovation and spilling the new technologies over as a public good will let the supplier combine the advantages of innovation and competitive downstream industry structure. Gaining control over key technologies may thus prevent the emergence of a bilateral monopoly with concomitant losses due to double-marginalization.

If the supplier cannot create a competitive downstream industry through strategic use of its R&D investment, then the returns to strategic R&D investments may be too small to warrant any such effort. This logic follows in principle the argument captured in Figure I.1. In the extreme case, an upstream monopolist in the supply sector would never try to preempt a downstream monopolist unless control over the new technology would allow the supplier to accommodate entry by more downstream producers.[12]

I.6 Contribution to the Literature

What is the contribution of this thesis to our knowledge and understanding of the innovation process? And in what ways can a better understanding of strategic appropriation and of the vertical dimension of R&D incentives contribute to managerial practice, for example in the formulation of R&D strategies? While these questions will be answered in more detail in the concluding chapter of the thesis, the present subsection provides the reader with several brief suggestions.

I emphasized above that the formal analysis of R&D incentives is usually based on one-sector models.[13] The relationship between R&D incentives in several industries cannot be captured in such models. One modelling assumption used to justify the one-industry approach usually states that all factors of production are procured from perfectly competitive sectors with elastic supply functions. This represents a convenient, but ultimately unrealistic starting point for a theoretical analysis. The view taken in this thesis is opposed to this simplifying modelling strategy. I assume that supplier firms can choose how much information to spill over to a downstream sector of buyer firms, given that such spillovers will cause changes in the demand for the commodity supplied by the upstream firms.

The two-sector models presented here reveal R&D incentives that would go undetected in a one-sector model. The models demonstrate that R&D incentives and industry structure in buyer industries may be subject to strategic manipulation by oligopolistic suppliers even if complex contracts cannot be written.[14] Upstream firms can afford to strategically manipulate related sectors because they can capture interindustry externalities, e.g. enhanced factor demand.[15]

The major novel element of the models is the characterization of spillovers as the consequence of an intentional provision of public goods information. All theoretical and empirical studies that I am aware of treat information spillovers between industries as the unavoidable and regrettable consequence of information production. The immediate implication of this view is that R&D efforts are less likely to be undertaken if they result mostly in the production of public goods knowledge. Conceivably, the opportunities for undertaking such activities are numerous, but the public goods problem renders many socially beneficial activities privately undesirable. The basic idea of the models in chapter III and IV qualifies this view to some extent. While it may not be possible to trade public goods knowledge, its strategic dissemination can create externalities beneficial for the producer of the public goods knowledge.[16]

The thesis also presents an empirical analysis in which I demonstrate that the composition of an industry's supply sector has strong implications for the industry's R&D intensity. While information spillovers cannot be measured directly, I find the theoretically predicted correlation between supply sector organization and downstream R&D intensity confirmed in my analysis. These empirical results are encouraging, because they demonstrate that a closer examination of vertical relationships may help to understand R&D incentives further. Some of the surprising differences in R&D behavior and productivity growth across industries (Nelson and Winter 1977) may become more explicable if the position of an industry within a vertical channel of production activities and strategic R&D incentives are explicitly taken into account.

A better understanding of actual firm behavior may ultimately help managerial decision-making as well. Successful outcomes are sufficient criteria in managerial practice to choose a certain course of action. However, a better theoretical understanding may in the long run help to improve the quality of managerial decision-making. The theoretical and empirical results described here constitute a step towards a prescriptive statement under which circumstances the strategic appropriation strategy discussed in this thesis can be profitable.

FOOTNOTES FOR CHAPTER I

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[1] The explanation that I propose for this behavior draws heavily on ideas developed by Corey (1956) and particularly von Hippel (1982) though the generalization to the strategic appropriation concept is my own contribution.

[2] In the case of materials producers - the case that initially caught my interest - the externality consists of an increase in demand for the materials producers' commodity product.

[3] See Cohen and Levin (1989) and Baldwin and Scott (1987) for a review of the state of the literature.

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

[5] Strategic aspects of licensing have been discussed (among others) by Shepard (1987), Gallini (1984) and Rockett (1990; forthcoming). However, licensing royalties play an important role in these models while the strategic appropriation mechanism discussed here relies fully on the strategic effects of a firm's R&D investment. R&D investments themselves may have a strategic role in oligopolistic interaction as Brander and Spencer (1983) point out.

[6] DuPont uses a classification framework for patented technology which seems very similar to the one proposed here for appropriation mechanisms. According to Gibson (1990, p. 78) patented technology can be used for three purposes. The most common case is that a patent is used for in-house purposes. Some patents are used to obtain revenues from licensing. The third option is a so-called "customer-use" patent.

[7] For a recent description of the adversarial character of buyer-supplier relationships in the semiconductor industry see the report by the United States General Accounting Office (1990).

[8] For an introduction to this literature see Tirole (1988, ch. 4). A more detailed survey is presented by Katz (1989).

[9] The supplier may be equally interested to prevent innovations that reduce its profitability. Though the thesis will not focus on this type of innovation, the reader will find some comments in chapter IV and in the concluding chapter VI.

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[10] In a previous paper (Harhoff 1988) I described some elements of the relationship between Apple Computer Inc. and producers of software compatible with Apple hardware.

[11] It is also conceivable that greater competition spurs innovation (Loury 1979) so that accommodating entry is unambiguously beneficial for the supplier. I will discuss here and in the body of the thesis the implications of a negative effect of entry on innovation incentives, since this assumption is more hostile to the strategic appropriation hypothesis.

[12] Loosely stated, this consideration suggests that the technological boundaries of firms should be closer to their manufacturing boundaries if vertical organization is characterized by bilateral oligopolies.

[13] The few exceptions from this rule include Binswanger and Ruttan (1978) and Mishina (1989).

[14] If admission into the downstream industry is regulated by contracts signed between supplier and buyer firms, then it is trivial that the upstream firms may be able to determine downstream industry structure and R&D incentives. "Exclusive territories" are an example for such contractual agreements between manufacturers and retailers.

[15] Strategic interaction between firms engaged in horizontal competition is one of the main subjects of oligopoly theory. The theory of vertical restraints has focused on the structuring of manufacturer-retailer relationships by manufacturers. Comparatively little attention has been given to the strategic use of R&D in vertical relationships.

[16] While this principle has not been applied to the analysis of R&D incentives, it is not completely new. It is well-known, for example, that large employers may finance regional school reforms "generously" if they can expect to have access to be better educated employees in the future.

Chapter II

Information Spillovers and Incentives for Research and Development - A Survey of the Literature

II.1 Introduction

This chapter provides a summary and discussion of recent theoretical and empirical research studying the interaction between information spillovers and incentives for research and development (R&D). The creation of new information is the dominant theme in the literature on innovation and R&D.[1] It is widely accepted that information has public goods characteristics which lead to a classical externality. Since producers of information cannot realize the full social return to their efforts, private incentives for the production of information are distorted and firms are likely to underinvest in R&D efforts.[2] At the same time, the public goods properties of information have positive implications, since information that spills into the public domain is available for each interested agent as an input for the generation of new products or knowledge (Spence 1984). Appropriability and access to external information are therefore often intricately linked, and one innovator's loss due to externalities is another innovator's gain.

An innovating firm often receives a considerable fraction of the information employed for cost reduction or product improvements from outside sources without compensating the originator of this information for its efforts. I will refer to such knowledge as *spillover information*.[3] The definition explicitly excludes knowledge transfer in contractual or market relationships while it clearly includes knowledge that is intentionally provided as a public good by institutions of the state, by non-profit research institutes, or other agents.[4] The definition is also wide enough to capture cases in which interested parties provide information spillovers with the intention to affect industry characteristics in their own favor.

To what extent spillover phenomena occur, whether they are intentional or involuntary, over which channels spillover information reaches a receiver, and to what extent this receiver can exploit the information is still very much unexplored. Most contributions in the economic literature treat the extent of spillovers as exogenously determined and their existence as involuntary. In most theoretical and empirical models the spillover mechanism (the source from which and the channel through which the information reaches the receiver) remains unnamed. The question of how recipients of spillover information capture and incorporate the received information in their own research and development efforts has received more attention recently, but even here theoretical and empirical work is still very much in its beginning. Finally, there has been no work on the *defensive efforts* firms undertake to prevent information from spilling over or competitors from getting access to spillover information. In this chapter, I will comment on each of these aspects and suggest some avenues for future research.

It is helpful to visualize the various elements of spillover knowledge that firms in a given industry may have access to. Researchers have conceptualized these information externalities as a two-step process in which private information spills over into a so-called "industry pool of knowledge" from where it can be recovered by other firms. While this view is clearly of a macroscopic nature (e.g. it completely neglects the possibility of exclusive interactions between firms), it has proven to be a satisfactory starting point for modelling efforts. Figure II.1 depicts this industry pool of knowledge as being composed of four components. First, technological knowledge may be produced by publicly funded laboratories, universities, or non-private R&D organizations. A second source of knowledge are sectors that are not directly linked to the industry in question. Patents obtained in one industry may, for example, suggest solutions to problems in a different industry since the usual industry classifications do not necessarily overlap well with technological distinctions.[5] A third source of information spillovers are industries which are linked through demand relationships to the industry analyzed here. Examples are suppliers of equipment, raw materials, and components, producers of complementary goods, or users of the industry's products. Finally, the private knowledge of firms in the industry may to some extent spill over into the industry pool and be accessible for competitors.

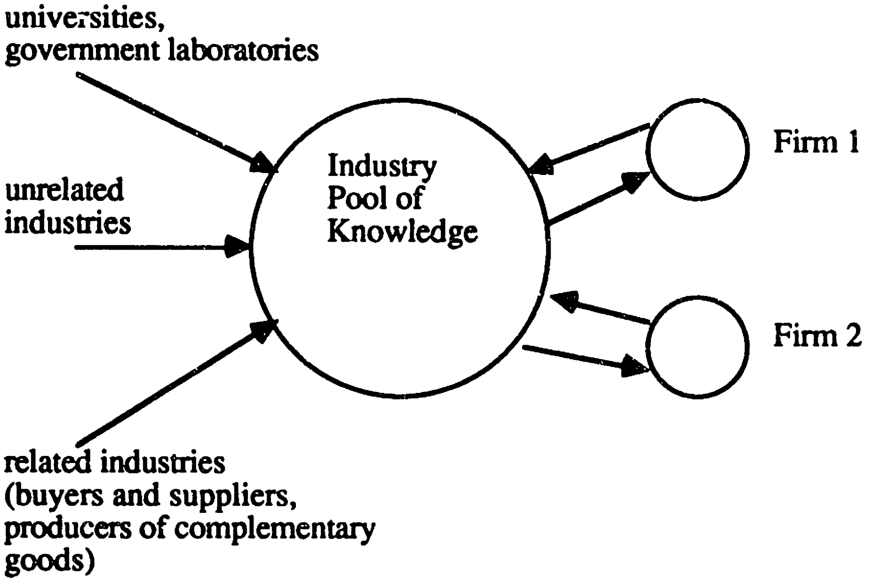

Figure II.1
Spillover Information - Contributors and Beneficiaries

The concept of an industry pool of knowledge that is accessible to all firms has several weaknesses. First, the channels (or mechanisms) through which a firm's proprietary information can reach other firms are given no consideration at all. And indeed, these channels have only found scant attention to date, mostly due to the difficulties in measuring their individual contributions to information dissemination. Mansfield (1985, p. 221) lists a number of possible mechanisms. For example, information can be transferred through personnel movements or informal communication among scientist and engineers. Suppliers and customers often have privileged access to firms with which they have business relationships and may be able to observe the technological capabilities of the respective firms. Sometimes the observer may have incentives to spread the information further, thus creating a spillover channel. In other cases competitors can obtain some information through inspection of patent applications or the reverse-engineering of products.

The concept of spillover knowledge as a homogeneous pool has a further shortcoming. It masks the fact that knowledge in the industry pool may not be readily employable for productive purposes and that it may not be conveniently gathered in one "location". The knowledge may be embodied in physical products such that it has to be reverse-engineered (von Hippel 1982). In other words, firms may have to undergo some effort to recover the knowledge. Both the extent to which a firm's private knowledge spills into the pool and the extent to which the competitors' and extraindustry knowledge can be recovered may depend crucially on the firm's own actions. Secrecy, for example, may help to reduce spillovers of private knowledge into the industry pool. Modifying a product such as to render reverse-engineering more difficult may help to make recovery of pool knowledge costly for competitors.

Leaving aside the question whether the recovery or decoding of information requires private efforts or not, figure II.1 may create the impression that spillover information is available in one "location". The economic literature has essentially followed this simplified perspective and abstracted from search costs that firms may incur when trying to profit from spillovers.[6] Empirical evidence suggests, however, that searching for technological solution concepts to solve a given problem is prevalent in many industries and that information is indeed scattered across various "puddles of information".[7]

These issues will be taken up in the following three sections. Section II.2 summarizes the recent theoretical literature on information spillovers in some detail. Section II.3 provides a survey of empirical models and econometric results.[8] Finally, section II.4 summarizes some case study evidence suggesting that firms frequently produce technological knowledge and intentionally spill it over into other industries. The providers of the spillover information appear to appropriate benefits from the production of the spillover knowledge via indirect or strategic appropriation mechanisms, e.g. enhanced factor demand or reduced input costs. The appendix to this chapter sketches two simple spillover models with protection and search efforts. These models will be extended in future work.

II.2 Models of Information Spillovers

The formal study of spillover effects has received much attention since the publication of Spence's (1984) seminal article on informational externalities and their effect on incentives for cost reduction. The Spence model is essentially static. The industry consists of *n* firms which can choose R&D expenditures that will increase their stock of knowledge. Unit costs c_i are a declining function of the firm's stock of knowledge z_i, i.e. $c_i = F(z_i)$ where it is assumed that $F'(z_i)<0$ and $F''(z_i)>0$. As in all spillover models, the most important specification concerns the interaction between privately generated knowledge and spillover information. Spence assumes that all firms make R&D investment M_i which contribute to firm i's stock of knowledge according to

$$(1) \qquad z_i = M_i + \theta \sum_{j \neq i} M_j \quad .$$

The effect of spillovers is captured via the parameter θ. If θ is equal to zero, then all firms utilize only their own knowledge and the specification is similar to the one used in Dasgupta and Stiglitz (1980). If θ is equal to one knowledge is a public good and each firm has access to and contributes to the industry's knowledge pool. The specification of the firm's stock of knowledge in (1) also implies that a competitor's knowledge is (up to the parameter θ) a perfect substitute for the firm's own knowledge.[9]

Spence assumes that in equilibrium the firms' profits are a function of their cost level which is implicitly determined by the ex ante R&D investments M_i and the industry's shared pool of knowledge. Let Q_i denote a firm's output and Q the industry output. The firm's level of output Q_i is a function of own knowledge z_i and of the knowledge z_j to which each competitor j, $j \neq i$ has access. Consumers have a utility function u(Q) and the inverse demand function is given by $p(Q)=u'(Q)$. Spence also allows for private R&D efforts to be subsidized by the government at the rate of s per private R&D dollar. Each dollar of R&D effectively costs the firm (1-s) dollars. Let z denote the vector of firms' knowledge. Firm i's earnings gross of R&D expenditures are then given by

$$(2) \qquad E_i(z) = Q_i(z)\, p(Q(z)) - c(z_i)Q_i(z) \quad .$$

Let $V_i = E_i - (1-s)M_i$ be the firm's earnings net of R&D costs. All firms know θ and take the R&D efforts of their rivals as given.[10] Maximizing V_i with respect to M_i yields *n* first-order conditions

$$(3) \qquad \frac{\partial E_i}{\partial z_i} + \theta \sum_{j \neq i} \frac{\partial E_i}{\partial z_j} = (1 - s) \quad .$$

The first term on the left-hand side captures the direct effect of firm i's R&D stock of knowledge on its level of production costs. The second term summarizes the effect that the stock of knowledge of all other firms has on firm i's profits. If we presume that a greater stock of knowledge will enhance own earnings and reduce the earnings of competing firms then it is clear that spillovers will lead to diminished private R&D investments. A fraction θ of each dollar of R&D expenditures flows into the knowledge pool available to competitors. Obviously, taking account of this effect will dampen the firm's R&D incentives. In a market equilibrium, spillovers will therefore reduce private R&D expenditures and subsequently the amount of cost reduction.

Spence then focuses in his paper on symmetric equilibria and shows that while incentives are reduced, the total costs for achieving a given cost reduction in an industry are also reduced by spillovers. Let $z^* = z_i^*$ denote a solution of (3) if firms are identical. Solutions for z^* can be found if the utility and cost functions are explicitly specified. Equilibrium R&D investments M^* will then be given by

$$M^* = \frac{z^*}{1 + \theta(n-1)} \quad . \tag{4}$$

Note that the overall R&D expenditures are nM^*. One can see from equation (4) that as *n* increases industry expenditures on R&D given by nM^* approach z^*/θ. Taking z^* as a measure for the level of cost reduction, the industry R&D costs of reaching this given level of cost reduction decline with the extent of intraindustry spillovers.

A further interesting element in Spence's paper is the discussion of the social cost of strong appropriability (i.e. high values of θ). The degree of appropriability (or the relative strength of an appropriability regime (Teece 1986)) is an important determinant of private incentives for research and development. Restoring appropriability by defining property rights to invention or innovation helps to restore incentives but also involves social costs. Assuming that the cost of transmitting knowledge (once it has been created) is zero the inventor will price the R&D good excessively high from a social point of view. The correct price should equal the marginal cost of transmitting the knowledge. Spillovers have in this view very desirable properties in that they maintain the socially optimal price for some fraction of the generated knowledge. To maximize welfare, Spence proposes not to strengthen appropriability, but to restore R&D incentives through subsidies. He demonstrates that market performance grows with spillovers if R&D incentives are restored by providing the socially optimal rate of subsidies.

Finally, Spence explores the implication of a somewhat atypical assumption in neoclassical work, namely that firms fail to anticipate the effect of their private R&D investments on their competitors' cost reduction. This analysis is motivated by the observation that some industries (like the semiconductor and electronic equipment sectors) appear to have high spillovers, yet perform relatively well in terms of "dynamic efficiency." Spence demonstrates that some ignorance on the part of firms could help to explain this phenomenon. If the spillover effect is not taken into account, then firms will invest more aggressively and high spillovers will be consistent with relatively strong R&D incentives.

Spence's view of appropriability as the cause of price distortions is based on the assumption that knowledge - once produced - can be replicated and transmitted to other potential users at relatively small expense. This assumption has often been used in theoretical models, but its excessive application has also invited strong criticism. Polanyi (1958) comments in great detail on the implications of "tacit knowledge". The orthodox view has also been criticized by Nelson (1980; 1982) and Kogut and Zander (1989).[11] Von Hippel (1990) points out that knowledge may be "sticky" for a number of reasons, and that transfer of information may involve considerable costs. Some forms of knowledge simply cannot be encoded economically for purposes of transmission. Von Hippel concludes that sufficient stickiness of data will make it profitable to move the problem-solver to the locus of problem data, rather than transfer data to the problem-solver. The implications of this suggestion for patterns of ownership and integration remain to be explored.[12]

A second aspect of Spence's model is that moral hazard problems of contract research (Williamson 1975) are not taken into account. But subsidizing R&D at the rates proposed by Spence (see his table IIIA) will invite opportunistic behavior by the recipients of such subsidies. If a firm's true R&D effort is unobservable or if the outcome of research and development is uncertain to some degree, then the efficiency losses due to the second-best properties of incentive schemes can be considerable. Once these costs are taken into account, monetary subsidization may be far less efficient than Spence's model suggests.

A final comment concerns the static structure of the model. If know-how spills over, then by definition it has been produced already in at least one firm. If knowledge production is bound to occur in some fixed sequence[13] this implies that one firm is in some sense ahead of other firms. The static nature of most spillover models can be justified by taking the view that such small differences in timing can be suppressed because long-run gains from R&D dominate short-term benefits.[14] But it is generally accepted that this presumption is often rather ill-suited to describe conditions under which technological progress takes place. The observation that firms in the electronics industry invest aggressively in R&D while facing considerable spillover effects can be therefore consistent with a world in which firms are mainly concerned with short-term gains. The fact that some know-how spills over after some period of time (e.g. the time necessary for reverse-engineering or designing around a patent) will not matter if the leading innovator can make a sufficiently large profit during the initial period. The dynamics of competition will therefore interact with the extent and timing of spillovers to determine R&D incentives. Simply to look at the correlation between incentives (measured as R&D intensity) and extent of spillovers in a cross-section of industries may result in misleading conclusions.[15]

The spillover model developed by Cohen and Levinthal (1989; 1990a; 1990b) provides a more detailed behavioral perspective than the Spence model. The model is supported by a number of behavioral theories of learning (Cohen and Levinthal 1990b). The key assumption made by Cohen and Levinthal is that access to spillover knowledge is not a free good for the firm. To utilize the existing spillover information the firm has to acquire an asset called "absorptive capacity". Absorptive capacity is modelled as a function of other *productive* R&D expenditures. As a consequence of this assumption, high spillover rates have two effects. On the one hand, spillovers create the R&D disincentives known from Spence's model. On the other hand, the information externalities will induce the firm to step up its R&D efforts in order to absorb more of the available spillover information. Cohen and Levinthal (1990a) show that the aggregate effect may well lead firms to respond to greater spillovers by making greater R&D investments.

Cohen and Levinthal model a firm's stock of knowledge z_i as

$$(5) \qquad z_i = M_i + \gamma_i(M_i)\,(\theta \sum_{j \neq i} M_j + T) \ ,$$

where by assumption $0 \leq \gamma_i \leq 1$, $\gamma_i' > 0$, and $\gamma_i'' < 0$. This specification resembles the one used by Spence, but implicitly incorporates extra-industry knowledge T (often called interindustry spillovers). Firms do no longer have free access to the pool of intra- and interindustry spillovers. The parameter γ_i measures the extent to which firms can profit from spillovers. If $\gamma_i = 1$ then the firm absorbs all knowledge available in the public domain. Conversely, if the parameter is equal to zero then the firm cannot exploit publicly available knowledge at all. Absorptive capacity increases with R&D expenditures M_i, but does so at a declining rate. Using the same terminology as in the summary of the Spence model, the firm's profit gross of R&D expenditures can again be written as

$$(6) \qquad E_i(z) = Q_i(z)\, p(Q(z)) - c(z_i) Q_i(z) \ .$$

The *n* first-order conditions now assume the form

$$(7) \qquad \frac{\partial E_i}{\partial z_i}\left[1 + \frac{\partial \gamma_i}{\partial M_i}(\theta \sum_{j \neq i} M_j + T)\right] + \theta \sum_{j \neq i} \left(\gamma_j \frac{\partial E_i}{\partial z_j}\right) = 1 \ .$$

Solving these n equations simultaneously yields the equilibrium solutions for R&D investments M_i^*.[16] For the purposes of this chapter, the most important implication of the Cohen-Levinthal model is that a firm's R&D efforts may well increase if the firm faces a greater rate of inter- or intraindustry spillovers. In other words, the sign of $\partial M_i^* / \partial \theta$ is ambiguous now, while it was unambiguously negative in the Spence model.

The learning process described by Cohen and Levinthal can be conceptualized as a decoding step. Information is readily available at the doorstep of the enterprise, but it is available only in encoded form. By enhancing its R&D capability, the firm will be able to decode the information and ultimately utilize a larger portion of industry pool information. Some of the results of this model are driven by the assumption that the knowledge used to decipher the external information simultaneously contributes to internal cost reduction efforts. In other words, it is productive knowledge that determines the firm's absorptive capacity.

The Cohen-Levinthal model provides an appealing explanation of a positive correlation between the extent of spillovers and a firm's R&D efforts. However, there are several alternative explanations that may also allow for this positive relationship between spillover rate and R&D efforts. I will address two possibilities here: the effect of search efforts and the possibility that firms may choose to counter spillovers by using a costly protection technique.

Consider first an economy in which external knowledge is readily available in decoded (i.e. employable) form, but the firm has to search for it. The search costs are of course different from R&D expenditures, but aggregate statistics will hardly reveal what kind of activities are untertaken by research scientists and engineers.[17] The managerial literature (Allen 1966; Allen 1977) suggests that a significant portion of resources available for an R&D project is indeed expended on search efforts. It seems also reasonable to presume that search efforts are not necessarily productive per se, i.e. they do not lead to cost reductions beyond those induced by the information found during the search. As I show in the appendix, the industry's R&D intensity may rise under these assumptions with greater spillovers, but for reasons different from those in the Cohen-Levinthal model. Let γ_i be a nondecreasing function of search effort S_i and let the firm simultaneously maximize its profits with respect to S_i and M_i, taking its competitors' search and R&D efforts as given. It can be shown that expenditures on search efforts increase with the rate of spillovers θ, while productive R&D efforts are reduced.[18] The joint effect on the sum of search and R&D costs is ambiguous as in the Cohen-Levinthal model. However, the cost reduction achieved in equilibrium will be smaller than in the Cohen-Levinthal case since there are no economies of scope.

Besides searching and learning, defensive and protective efforts may also be important determinants of a firm's R&D incentives. Apparently, the extent to which firms defend their technological know-how differs greatly across industries and technologies, but to this point there has been little systematic documentation or even analysis. Firms in a given industry may undertake defensive efforts for two reasons. The first is to prevent information from leaking into the industry's pool of knowledge. Formally, this can be modelled as a firm-specific spillover rate $\theta_i(.)$ which is nonincreasing in some form of protection effort P_i. The second possibility for firms to prevent competitors from gaining access to spillover information is to raise the competitors' costs of extracting information. For example, some fraction of a firm's R&D budget may be used to increase other firms' cost of reverse-engineering a product.[19] These efforts do not have to result in perfect protection - if the cost of accessing spillover information can be raised sufficiently, then protective efforts may restore appropriability of private R&D efforts substantially. Such reasoning suggests that both θ_i (the extent of spillovers from firm i's R&D effort into the industry pool) and γ_j (the extent to which firm j has access to the industry pool) are decreasing functions of the firm's protective effort P_i. Protection efforts of this form may also have an interesting filtering effect in that private information of high value is presumably better protected than knowledge of minor importance. The quality of knowledge in the industry pool is then likely to be inferior to best practice knowledge safeguarded within the competing organizations.

In all likelihood, we will find a combination of learning, search, and protection in real-world situations. Industries in which technological progress greatly depends on various scientific disciplines are probably best characterized by the learning model, while industries in which R&D activities mainly involve engineering and technical problem-solving are probably better described by a search model.[20] Note again that search effort S_i, productive R&D M_i , and protective measures P_i may all contribute to the firm's R&D bill. Aggregate R&D data will not always allow us to generate a detailed empirical picture. Further advances in our knowledge regarding the composition of R&D efforts are therefore most likely to come from industry studies.

Besides abstracting from search and protection effects, the Cohen and Levinthal model and the Spence model share two important assumptions. The first is that all external knowledge is a substitute for internally generated knowledge. In the Spence model, substitution is perfect, while the elasticity of substitution is a function of private R&D expenditures in the Cohen-Levinthal model. Second, industry structure (the number of firms) is given exogenously in these two models, i.e. the firms R&D decision does not affect industry structure at all.[21] Levin and Reiss (1988) employ a very different set of assumptions and develop an extension of the Dasgupta and Stiglitz (1980) model. In their model intraindustry spillovers are imperfect substitutes of the firm's own R&D. Furthermore, free entry allows firms to enter the industry until profits are driven to zero. Both assumptions have distinct implications.

Levin and Reiss maintain the specification for the firm's pool of knowledge in equation (1), but they suggest that unit variable production costs are given by a function $c_i = c(M_i, z_i)$. For example, in their empirical work they employ the iso-elasticity specification $c_i = A_c M_i^{-\alpha} z_i^{-\beta}$ where A_c is a scaling factor and α and β are the elasticities of cost with respect to private R&D and the industry pool of knowledge. In this specification, own R&D M_i may add both to the firm's own idiosyncratic research capability and the firm's R&D pool z_i. Their specification of spillovers allows them to distinguish two effects: the extent of spillovers and the productivity of intraindustry spillovers. As in the Spence model, a greater extent of spillovers θ leads to a reduced R&D intensity. However, R&D intensity increases with β, the *productivity* of spillovers. Levin and Reiss take a much simpler perspective regarding inter-industry spillovers by assuming that they are always complementary to the firm's own production of knowledge. This assumption appears to contradict some of the empirical results obtained by Bernstein (1989) as discussed in section 3 of this chapter.

Reinganum (1981) provides the only model that studies the effect of spillovers in a model of timing. Firms acquire knowledge over time in Reinganum's model. Knowledge acquisition is described by the differential equation $\partial z_i(t)/\partial t = u_i(t,z_i(t))$ where $z_i(t)$ is firm i's stock of knowledge at time t and $u_i(t,z_i(t))$ is the firm's rate of knowledge acquisition. The date of concluding a research project successfully is a stochastic function of the stock of knowledge and, as usual in models of timing, Reinganum assumes that the amount of knowledge required to succeed is distributed exponentially. Reinganum assumes further that some knowledge acquired by firm i during the patent race can spill over from firm j to firm i according to $\partial z_i(t)/\partial t = u_i(t,z_i(t)) + \rho\, u_j(t,z_j(t))$. For the polar case in which all knowledge is transferable across firms (i.e. there is no duplication or idiosyncrasy) and complete spillovers ($\rho=1$) Reinganum shows that spillovers lead to a diminished rate of knowledge acquisition. On average, innovation will occur later than is socially optimal. However, she also notes that for some parameter values innovation can occur stochastically earlier due to the spillover effect.

The assumptions used in the Reinganum model are based on a certain conceptualization of the nature of information and the timing of research projects. Note first that the time profile of knowledge acquisition can be chosen by the decision-maker in the Reinganum model, i.e. a project can be arbitrarily decelerated or accelerated at any stage. While this assumption provides results of some mathematical generality, it is likely that the decision to accelerate or decelerate a real-world R&D project causes fixed costs of some sort which are not captured in Reinganum's model. Second, Reinganum's assumption that all knowledge is transferable in combination with symmetric strategy profiles implies that a unit of knowledge produced by firm i at time t can be utilized by firm j at at a later point in time. Essentially, this view requires that the research project is not subject to strong sequentiality constraints or that the required sequence of research steps at firm i and firm j are different. If sequentiality constraints are at work then firm i utilizing spillovers from firm j's R&D efforts always implies that one firm i is ahead of the other firm. To express this point in greater clarity, assume that both firms a solving a rectangular jig saw puzzle. If both firms can start at opposite ends of the puzzle, then spillovers will be productive since they are not duplicative. If both firms have to start with some piece of the puzzle and follow some fixed sequence of steps then all spillovers simply duplicate private R&D and the utilization of spillovers would require a deviation from symmetric strategy profiles.

Spence, Cohen and Levinthal, Levin and Reiss, and Reinganum describe the spillover process at an aggregate level. The particular characteristics of specific spillover channels are not taken into account in these models. Detailed studies of spillover mechanisms are still scarce, but some promising attempts have been made in this direction. Mishina (1989) analyzes the incentives of downstream firms to develop inputs jointly with a monopolistic supplier despite the threat that suppliers may leak private information to competitors. Mishina assumes that firms in the downstream industry (incumbents and entrants) have idiosyncratic production processes. If firms choose not to cooperate with the monopolistic supplier then inputs will not be tailored to the firm's idiosyncratic needs and marginal costs will be relatively high. Conversely, if a downstream firm decides to develop inputs jointly with the supplier, then the resulting low-cost production technology is available to any entrant. Contracts are assumed to be unenforceable, since the downstream firm cannot observe its competitors' process equipment or the supplier's product shipments. Therefore joint input development leads to complete revelation of the downstream firm's technology.

In the Mishina model joint development reduces the cooperating firm's costs (and subsequently industry costs) but it also allows competitors to enter the industry. The reduction in industry costs leads to enhanced efficiency and greater industry profits. Ceteris paribus, it provides a positive incentive for joint development. Conversely, the negative incentive effect from enhanced competition reduces the downstream firm's incentives to cooperate with the supplier. A firm may well forego its cost advantage relative to other firms if the reduction in industry costs and the concomitant increase in industry profits are sufficiently high to compensate for the losses due to enhanced competition. The Mishina model illustrates an interesting effect of idiosyncrasies in production. If the solutions to the technological puzzle of cost reduction are distributed across industries (i.e. costs of vertical integration are too high) then the exploitation of the downstream firm's process potential requires greater revelation of private information than would occur without idiosyncratic production technologies. Although Mishina tailors his model to a setting with a monopolistic supplier, two downstream incumbents and a number of potential entrants, one can easily obtain similar results for another situation. Consider a monopsonistic buyer who faces two suppliers with different costs. Suppliers may have an incentive to share information with the downstream buyer if coordination leads to greater demand for the intermediate product. These incentives may survive even if the downstream monopsonist can leak the information to upstream entrants, provided that the gain in upstream profits is sufficiently large to compensate for losses from enhanced competition.

There is some similarity between the Mishina model and licensing models in which a monopolist invites competition in order to induce demand growth. But in the Shepard (1987) and Farrell and Gallini (1986) models, the incentives for admitting entrants into the industry are "stronger" than in Mishina's model due to the incumbent's ability to charge licensing royalties.[22] Mishina does not consider this possibility, and his conclusions therefore depend on relatively large cost reduction effects (i.e. large differences between the minimum cost achievable when process potential is fully exploited and the cost level achievable without cooperation with the supplier).[23]

II.3 Econometric Results

Some of the models summarized above have been subjected to empirical tests, and additional empirical models have been developed to measure the effects of spillovers. Levin and Reiss (1988) use industry aggregates from the Line-of-Business (LOB) database of the Federal Trade Commission (FTC) to test a model that nests several specifications of spillover effects. In particular, their model allows them in theory to distinguish between the Dasgupta-Stiglitz formulation (no spillover effects), the Spence model, and their own model in which intraindustry spillovers are potential complements to the firm's own R&D. Unfortunately the FTC data do not allow them to estimate spillover effects with great precision so that the Dasgupta-Stiglitz formulation cannot be rejected for either process or product innovation.[24]

Cohen and Levinthal use the FTC dataset at the LOB level and employ the survey responses obtained by Levin et al. (1987) to measure the effect of technological opportunity and spillovers on R&D intensity. Their empirical model imposes considerably fewer restrictions on the data than does the Levin-Reiss model. Cohen and Levinthal estimate a linear relationship between R&D intensity as the dependent variable and measures of technological opportunity, appropriability, and demand conditions. The measures of technological opportunity include the relevance of eleven basic and applied scientific fields to innovative activity in the respective line of business[25] and the knowledge contributions by suppliers of equipment and materials, user industries, government laboratories, and university-based research. The appropriability measures employed by Cohen and Levinthal are again taken from the Yale survey. Other control variables include the estimated price elasticity of demand, the income elasticity, the percentage of the industry's property, plant, and equipment installed within five years prior to sampling, and a measure of industry growth. The regression results confirm by and large the basic proposition of the Cohen-Levinthal model that greater relevance of external knowledge will induce firms to step up their own research efforts. However, for some sources of external knowledge and scientific disciplines the estimated regression coefficients are actually negative. Cohen and Levinthal find that greater relevance of agricultural science, geology, and metallurgy exerts a significant negative effect on the line of business's own R&D intensity. Furthermore, greater contributions by suppliers of equipment and materials have a strong negative effect on the research intensity of the line of business.[26] Cohen and Levinthal argue that suppliers tend to provide rather targeted external information, such that firms have no need to improve their absorptive capacity. In the presence of diminishing returns to R&D, the existence of targeted external knowledge will lead to substitution effects and therefore reduce the R&D intensity of the line of business. Cohen and Levinthal also find some support for their proposition that R&D intensity may actually increase with greater spillover rates. Regression results suggest that this is the case in the chemicals (SIC 28) and electrical equipment (SIC 36) industries.

Jaffe (1986) follows an earlier proposal by Griliches (1979) and derives a measure of technological proximity between firms from the classification of the firm's patents into broad patent groups. The firm's patenting activity allows Jaffe to compute a vector with 49 elements, each of which indicates the strength of the firm's R&D efforts in the respective technological area. Jaffe uses these vectors to construct a measure of "technological proximity" between firms. He hypothesizes that only firms who are close technological neighbors are in the position to profit from each other's stock of knowledge via information spillovers. In his model each firm has access to a spillover pool which is given as the weighted sum of all other firm's R&D expenditures, using the proximity measures as the weights. Jaffe also uses the 49-element vectors of technological activity in a clustering procedure to identify groups of firms who presumably face similar technological opportunities. However, as Cohen and Levin (1989, p. 1084) point out, these cluster variables did not perform better than conventional industry dummy variables.

Jaffe estimates three equations. The first relates the firm's patent count to its R&D expenditures and access to information spillovers. The second and third equations model profits and market value (Tobin's *q*) as a function of R&D, spillover information, capital, market share and industry concentration. In the patent equation, the coefficients on the information pool variable (i.e. the pool of spillover information a firm has access to) and the coefficient on the interaction between a firm's own R&D and the pool measure are positive and highly significant. The result regarding the interaction term can be interpreted in accordance with the Cohen-Levinthal learning hypothesis: the greater the firm's own R&D efforts, the stronger is the positive effect of spillover knowledge on the firm's innovative output.[27] Evaluating both effects for the firm with mean log(R&D), Jaffe computes a patent elasticity of 1.1 with respect to spillovers. Using profits and Tobin's *q* as dependent variables, Jaffe finds that the size of the spillover pool itself exerts a negative effect on these measures, while the interaction effect is again positive. Again calculating the effect for the firm with average private R&D expenditures, the elasticity with regard to the spillover pool amount to .1 for profits and .05 for Tobin's *q*. Thus the effect of spillovers appears to be heterogeneous. Firms with R&D efforts considerably below the sample mean are more likely to suffer profit and market value losses from the existence of spillovers, while firms with relatively high R&D investments profit from the externalities. In a second paper Jaffe (1988) considers the effect of spillovers on the private R&D incentives of firms. He finds that spillovers from close technological neighbors tend to be complementary to the firm's own R&D efforts, i.e. a firm's R&D expenditures are increasing with the size of the spillover pool the firm has access to.

Jaffe's results - though circumstantial - provide strong empirical support for the view that informational externalities have significant economic effects and influence the spillover recipient's welfare. An important caveat should be noted, however. The concept of technological proximity is based on patent measures which only provide a partial picture. While Jaffe (1986, p. 989) states that "patents have repeatedly passed tests of their economic relevance", one can hardly fail to overlook their imperfection as a measure of technological output. Cockburn and Griliches (1988, p. 422), for example, note that "(...) there is some interesting information in patent counts, but it is subject to much error. Data on R&D expenditures, where available, are stronger measures of input to the process by which firms produce technical innovation than patents are of its output."[28] Jaffe's use of combined measures of technological opportunity and propensity to patent alleviates the weakness to some degree, but in turn it reduces the interpretability of results concerning the nature of technological opportunities.

A rather different approach to the measurement of spillover effects has been taken by Bernstein (1988; 1989) and Bernstein and Nadiri (1988; 1989). In their various papers they employ longitudinal data and duality properties in order to estimate the effects of either intraindustry or interindustry spillovers or both on the coefficients of a suitably defined cost function that includes R&D as a factor of production.

Bernstein and Nadiri (1989) study the effect of intra-industry spillovers in four US industries. Interindustry spillovers are not considered here. Their model is based on the theory of dynamic duality and allows them to distinguish three distinct implications of intraindustry spillovers: the reduction of production costs, effects on factor demand functions, and the effect on the rate of capital accumulation. Bernstein and Nadiri can not detect any complementarity effect between spillovers and the firm's investment in physical and R&D capital. Quite to the contrary, in all four industries (chemicals, instruments, machinery, petroleum), spillovers have a negative effect on the rate of investment and are actually capital-reducing, both for R&D and physical capital. Variable and average costs decrease with increasing R&D spillovers, as expected. On average, a 1 per cent increase in spillovers leads to a reduction in average cost of .2 per cent.

In their (1988) paper, Bernstein and Nadiri focus on interindustry spillovers between five US industries (chemical products, non-electrical machinery, electrical products, transportation equipment, and scientific instruments). They use a truncated translog cost function in which each industry's R&D capital stock is included as a separate spillover source. Variable cost declines in all industries as a consequence of interindustry spillovers. For example, in 1961 the reduction in average cost responding to a 1 per cent increase in spillovers ranged between 0.029 per cent in non-electrical machinery and .208 per cent in chemical products. The spillover benefits enjoyed by these industries stem in most cases from a narrow range of sources, i.e. from either one or two other sectors. For example, the chemical products industry experiences significant interindustry spillovers from the scientific instruments industry, but apparently none from the other sectors studied here. Bernstein and Nadiri also find evidence for factor-biasing effects of interindustry spillovers in this paper. Essentially the same methodology is employed in Bernstein (1989) for nine Canadian industries and the results are by and large consistent with those reported earlier.

Only in Bernstein (1988) are interindustry *and* intraindustry spillovers included simultaneously in an empirical study of this type. Spillovers of both types are found to reduce average cost of production. Surprisingly, the effect of interindustry spillovers appears to be much stronger than that of spillovers within the industry. Furthermore, it appears that interindustry spillovers are in all cases *substitutes* for private R&D efforts by firms within the industry. Conversely, intraindustry spillovers are complementary to private R&D efforts for firms operating in industries with relatively large R&D expenditures, while they work as substitutes for private R&D in industries with a low R&D intensity.

The Bernstein-Nadiri approach can also be used to quantify the difference between social and private rates of return to R&D. Somewhat surprisingly, in Bernstein (1988) the social return to interindustry spillovers is rather small (on the order of 2 per cent) despite their strong effect on average cost, while intraindustry spillovers are responsible for a large gap between private and social returns to R&D.[29] But in all of these four studies the overall social rate of return to R&D exceeds the private rate by a factor of two or more. These estimates are of similar order as those produced by Mansfield et al. (1977), Griliches (1964), or Evenson and Kislev (1973).

II.4 Intentional Production of Interindustry Spillovers

- Case Study Evidence

Much of the literature summarized in the previous two sections implicitly assumes that information spillovers occur against the will and intention of the spillover source. Information is assumed to "leak out" to other sectors or competitors, thereby creating a wedge between social and private rates of return. But it is also well-known that patterns of voluntary information transfer exist in and among several industries. No matter whether one decides to call these phenomena spillover effects or voluntary information transfer, the empirical studies considered above simply cannot distinguish between the two types of transfer. The rate of spillovers implied by these studies may therefore contain a significant portion of intended information transfer.

Regarding intentional intraindustry information transfers, Baumol (1990) refers to groups of firms which exchange technological know-how as "information-sharing cartels". Based on some norm of reciprocity firms informally exchange information in a setting similar to a bartering market.[30] These interactions can be conceptualized as a repeated Prisoner's Dilemma game. As long as the benefits from defection do not outweigh the future gains from cooperation (including the avoidance of punishment by being excluded from future exchanges) the transfer pattern is likely to be stable. Formally, a suitable version of the Folk Theorem suggests that cooperative outcomes can be supported by subgame-perfect strategies if players are sufficiently patient.

Other patterns of voluntary information transfer between firms in different industries do not depend on reciprocity of information exchange. Technical change in one sector of the economy may affect other sectors in various ways. Consider for example the case of a monopolist who sells computer hardware. Innovations in sectors in which complementary products (e.g. software) are produced have direct implications for the welfare of the monopolist. Similarly, the profit rate of suppliers of intermediate goods depends partly on the extent and speed of innovation in the sectors using the intermediate good as an input. Such linkages between sectors create incentives for firms to influence the rate and direction of technical change in industries other than their own. These interdependencies can be interpreted as a kind of principal-agent relationship. In the case of the computer industry, the hardware monopolist can be seen as the principal who tries to induce firms in the complementary goods sector (the agents) to provide the optimal amount (or speed) of innovative effort.

Case studies that focus on this interdependence can often be found in the managerial literature on innovation, and in particular in the marketing and purchasing contributions. A detailed study of marketing practices for the development of markets for new materials has been provided by Corey (1956). In his case studies, Corey analyzes in great detail 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. In some cases the upstream supplier created *design tournaments* for downstream producers: In the case of Dow Styron, for example, the quality of plastic toys designed by downstream producers was evaluated in a Dow-sponsored contest and "winners" were allowed to use the Dow brand name on their products.[31] Conceptually, these supplier efforts can be interpreted as attempts to change the downstream rewards to innovation or to supply technological knowledge that reduces the cost of innovative efforts.

The upstream firm may not only be concerned with the rate of technical change, but also with the rate of entry into the downstream industry. Corey notes that in the case of fiberglass-reinforced pipe, several downstream firms were trying to obtain patents on the production process, but in two cases the research effort was undertaken jointly with Owens-Corning and patent rights were shared. The fiberglass producer was therefore in a position to prevent incumbent firms from erecting barriers to entry by licensing the technology to new entrants. Obviously, there is a basic conflict between both parties in such joint research efforts. Corey (1956, p. 53) comments that "the fabricator-customer who does extensive technical development work has the objective of strengthening his own position in the market against existing and potential competitors. The materials producer, on the other hand, will often want to attract a large number of end-product manufacturers into the market to speed market growth and to develop outlets for his materials. In so doing, the materials producer is bringing in firms to compete for market share with the original fabricator-customer."[32] Competition for the vertical distribution of rents in the channel may induce the upstream producer to accomodate entry by additional firms or to prevent an increase in downstream market power (e.g. in the form of patent monopolies). In extreme cases, a patent race between the upstream supplier and downstream firms may ensue. The supplier may try to acquire control over a new downstream technology in order to prevent a restriction of entry.

Leenders and Blenkhorn (1988) provide another set of case studies in which large buyer firms seek to induce technical change among their suppliers. Some of their examples provide clear evidence for asymmetries in the information structure. The buyer firm often has superior information how a particular component or material should be manufactured. Leenders and Blenkhorn argue that instead of waiting for a supplier to offer such an input, downstream firms should use a "reverse marketing" strategy and induce the necessary technical change among their suppliers. However, other strategic motivations may lead the downstream firm to spill technology over to the supply sector. In one particular example (Leenders and Blenkhorn 1988, p. 36), a downstream firm chose to accomodate upstream entry in order to break a pattern of price collusion among its suppliers. The downstream firm provided extensive technical assistance and reduced the cost of entry sufficiently to accomodate a new supplier firm.

Peck (1962) studied the sources of innovations in four technical areas of the aluminum industry (joining, finishing, fabricating, alloys). He found that most contributions to joining, finishing, and fabricating originate with equipment manufacturers, while primary producers of aluminum accounted for most of the novel aluminum alloys. However, aluminum producers were also active in joining and fabricating techniques. As Peck (1962, p. 288) notes, "the primary producers realize gains form inventions in fabricating techniques through the increased demand for aluminum." While Peck notes that primary producers of aluminum have not played a dominant role in the development of new processes, he also points out their importance in the development of new aluminum-using products. He suggests that returns to the aluminum producers from new product applications have been more immediate and certain than returns from improved processing technologies.

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. However, relationships between the aluminum producer and its customers were not without adversarial elements. As Graham and Pruitt (1990, p. 368) point out, "while Alcoa continued to avoid competing directly with its customers, it served notice on the foot-dragging container industry that it would not shrink from encouraging and giving technical assistance to new entrants." The control over can-making technology was costly to acquire (Graham and Pruitt 1990, p. 367), but it was used by Alcoa as a strategic asset to promote the adoption of its aluminum can technology.

Two other detailed industry studies have been provided by VanderWerf (1990a) 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. VanderWerf's sample consists of 14 innovations in plastics processing and 12 innovations in industrial gas applications. Materials suppliers were identified as the innovators in five cases in plastics processing and in 4 instances in industrial gas applications. VanderWerf also suggests that materials suppliers apparently did not charge licensing fees for their innovations. They profited from their innovative efforts by experiencing enhanced demand for their commodity.

This list of cases in which firms make technological information freely available to enterprises in vertically related sectors is not exhaustive. In another paper (Harhoff 1988), I described spillover phenomena in the relationship between Apple Computer (a producer of computer hardware) and firms that produce software compatible with Apple's hardware. Other interesting examples of intentional spillover production can be found in the case of gas and electric power utilities. The electric power utilities in the

United States founded the Electric Power Research Institute (EPRI) in 1972 with the intention "to develop and manage a technology program for improving electric power production, distribution, and utilization."[33] A number of EPRI's research projects are defined as "customer systems research" and provide users of electric power with technological information.[34] Gas utilities have founded a corresponding institute, the Gas Research Institute (GRI), which is also involved in developing novel technologies and information for use by customers of gas utilities.

As in the other cases discussed in this section, these examples appear to involve an exchange of externality benefits. Upstream suppliers produce technical information that leads to cost reductions, product improvements, or enhanced entry rates in the sectors processing the materials. This knowledge transfer can be conceptualized as an interindustry information spillover. In return, the upstream producer receives a benefit spillover from enhanced factor demand.[35] Circumstances under which such behavior is likely to emerge are studied in formal models in the next two chapters.

FOOTNOTES FOR CHAPTER II

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[1] The terms "information" and "knowledge" are used as synonyms in this chapter.

[2] Privately generated information can reach the public domain in various ways. The "wedge" between private and social returns to R&D has been studied extensively by Mansfield (1977, 1985). See also Trajtenberg (1990) for a detailed study of the economic effects of computer tomography technology.

[3] The term spillovers is not only used for informational externalities but also in cases where an innovator cannot capture the full social value of its innovation. Innovators are usually not in a position to determine and extract the full reservation value from buyers even if the innovator's monopoly position is guaranteed. The monopolist with power of perfect price discrimination is a helpful textbook metaphor, but rarely found in the real world. Given this "imperfection" the utility that a buyer derives from purchasing a good is often higher than the price charged by the seller, i.e. social and private returns to innovation are different. For example, Bresnahan (1986) analyzes the *benefit* spillovers accruing to the insurance industry from the introduction of mainframe computers. I will use the term "spillovers" in lieu of "information spillovers" except when clarity of exposition requires the more precise distinction.

[4] Some may object that the term "spillover" should be restricted to involuntary information dissemination. I find that definition rather narrow since the economic effects of information dissemination are the same for the receiver, no matter whether information is provided voluntarily (as a free good) or involuntarily. The empirical spillover models summarized in this chapter do not distinguish between voluntary and involuntary spillover production, but the actual estimates are likely to reflect the economic effects of both types of spillovers.

[5] Schmookler (1966, p. 20) points out that within the same classification group of patents he found patents for toothpaste tubes and manure spreaders. Conceivably, firms in different industries can benefit from similar technological information. This observation motivates Jaffe's (1986)

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construction of a measure of "technological proximity" (see section 3 of this chapter).

[6] Increasing a competitor's search costs may be another defensive strategy for firms. In the tire industry, for example, it is industry practice to decompose proprietary production machinery into smaller units which are built by external equipment makers. The tire producer then assembles the components in-house. It is well known that this procedure is more expensive than ordering the complete production system from one equipment maker. However, firms intentionally incur some costs here in order to *scatter* information regarding their proprietary production technology.

[7] Allen (1966; 1977) presents several interesting results regarding the nature of technological problem-solving. See also von Hippel (1988b).

[8] The term "empirical model" is used here to describe efforts of measuring spillover effects without making normative statements, i.e. it refers to pure measurement models.

[9] The parameter θ only measures the net effect of spillovers, i.e. Spence does not model separately how private information gets into the industry pool and how (and to what extent) competitors gain access to it. Therefore, one could also interpret θ as a measure of idiosyncrasy of knowledge. While the firms in the industry see all of their competitors' knowhow, they cannot apply it due to idiosyncrasies between their production environments. A high spillover rate (i.e. a small degree of idiosyncrasy) can then be thought of as having the effect of standardizing the technological know-how of the industry.

[10] Note that Spence implicitly uses an equilibrium concept with sequential decision-making. Firms set their R&D levels anticipating the future output or price decisions.

[11] There are also some empirical studies suggesting that transfer costs may be considerable, even in cooperative settings. For example, Teece (1977) found that transfer costs were on average 19 per cent of total project cost and that they ranged between 2 and 59 per cent. However, Teece's results concern international transfer of know-how and may therefore reflect institutional differences, differences in labor skills, and other factors. See also Mansfield et al. (1982) for an empirical analysis of transfer costs.

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[12] A direct implication is that greater "stickiness" of information leads to greater specificity of the intellectual assets employed in technical problem-solving. According to Williamson (1975), firms should then prefer integration over market transactions.

[13] For example, assume that two firms have to generate some element of information at the beginning of the R&D project before any other information can be generated. Then a spillover of this initial information from firm 1 to firm 2 is valuable for firm 2 only if firm 2 is lagging in its own efforts.

[14] One would expect that a similar perspective is then taken with respect to industry structure, i.e. that entry is possible and that profits will be dissipated in the long run through competition. However, industry structure is exogenously given in Spence (1984).

[15] Cohen and Levinthal (1990b, p. 139) acknowledge this problem by noting that "(...) appropriability conditions are often considered to reflect the degree to which valuable knowledge spills over out into the public domain. The emphasis here is on valuable knowledge, because if a competitor's knowledge spills out but the competitor has already exploited a first-mover advantage in the marketplace, this knowledge is no longer valuable to the firm and does not constitute a spillover by our definition." However, this conceptual distinction is usually not reflected in static models of spillovers.

[16] Cohen and Levinthal (1990a) discuss additional details of their model and provide a numerical example.

[17] Cost allocation to R&D or other firm activities (e.g. technical services for customers, marketing, training) is a difficult matter. Most western countries have adopted the guidelines proposed in the 'Frascati Manual' (OECD 1981). However, these guidelines are very complex and it is unlikely that firms follow them in detail. See also Freeman (1982).

[18] See the appendix for a more detailed description of a model involving search for spillover information.

[19] In some industries such activities are standard practice, e.g. in the semiconductor industry they are known as "potting". "Potting" was originally only a packaging technique to protect semiconductor chips from

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pollution, but it emerged later as a strategy to make the analysis of chips more difficult.

[20] Allen (1977) suggests that excessive searching may occur due to incentive problems within the firm. While it is nearly costless (in reputation terms) for an individual engineer to ask suppliers and other outsiders for solution proposals to technical problems, posing the same questions within the firm may undermine the engineer's reputation. This argument also suggests an interesting link between information spillovers and the internal management of the innovation process.

[21] Both models also assume that decision-making is sequential, i.e. the output or price decision is preceded by the R&D decision. Conversely, Levin and Reiss (1988) follow Dasgupta and Stiglitz (1980) in assuming a simultaneous choice of output level and R&D effort.

[22] Allowing for side payments (licensing fees) would strengthen Mishina's results. The downstream industry leader could ask the supplier for royalties which the supplier in turn extracts from entrants.

[23] To attain joint development as an equilibrium strategy without such licensing fees the Mishina model requires idiosyncrasies to have relatively large effects on costs. Take for example the case of an incumbent monopolist facing the demand curve $p(Q)=\sigma Q^{-\varepsilon}$.where ε is the inverse of the price elasticity of demand. Let costs be c^+ if no joint input development takes place. The monopolist anticipates that its minimum cost technology c^- would spill over to m entrants if it cooperated with the upstream supplier. For joint development to occur in equilibrium, a firm's profits with technology c^- in an n-firm oligopoly ($n=m+1$) have to be higher than the monopoly profits with technology c^+. If the oligopolists entertain Cournot conjectures this condition can be written as

$$c^+/c^- > (\varepsilon/n^2)^{(\varepsilon-1)/\varepsilon} \cdot (1-\varepsilon)/(1-\varepsilon/n) \quad .$$

For the duopoly case ($n=2$) one can easily calculate the required cost ratio for a given elasticity of demand. For example, if $\varepsilon^{-1} = 2$ then c^+/c^- has to be greater than 2.66 to satisfy the condition. If $\varepsilon^{-1} = 5$, $c^+/c^- > 1.257$ is required. The critical ratios are even larger for $n>2$ and they are decreasing in the elasticity of demand. It should be noted that the results are different once the initial industry structure is a duopoly, but the general relationship between demand elasticity and required cost reduction effects still holds.

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[24] The nonlinear nature of the Levin-Reiss model complicates the testing of these hypotheses considerably. For details see Levin and Reiss (1988, p. 551 and p. 553).

[25] The applied sciences are agricultural science, applied mathematics and operations research, computer science, materials science, medical science, and metallurgy. The basic scientific disciplines are biology, chemistry, geology, mathematics, and physics. The relevance of these disciplines for the respective line of business is evaluated on Likert scales (Levin et al., 1987).

[26] Cohen and Levinthal aggregate the measures for the contributions by suppliers of research equipment and production equipment. It is likely that the first group has a positive effect on the firm's R&D efforts in the sense that improved R&D equipment is a complement to private efforts.

[27] As Jaffe notes, there are of course alternative explanations. For example, firms may simply patent more if they compete with a larger number of competitors. For a detailed analysis of the firm's propensity to patent see Scherer (1983).

[28] Weighted patent measures as analyzed by Trajtenberg (1990) could conceivably alleviate some of the weaknesses. But in principle such weighting schemes only reduce the errors-in-variables problem in the observable portion of the firm's technological activities. To the extent that innovative output is not patented, even improved measures of patenting will not solve the basic measurement problem. Leaving aside the weaknesses of patents as a measure of innovative output, it appears that patents may provide a more satisfactory basis for determining the firm's technological position (relative to other firms).

[29] The social returns to interindustry spillovers reported in Bernstein and Nadiri (1988) appear rather small when compared to results for Canadian industries in Bernstein (1989, p. 326).

[30] These observations originate largely with von Hippel's work on know-how trading in the minimill steel industry. For details see von Hippel (1988a, p. 76), Carter (1989), and Schrader (1990; 1991).

[31] Corey (1956, p. 162) describes this process as follows: "On approval of an article by the Product Evaluation Committee, the molder was authorized to identify each unit of this article he produced by affixing to it a label

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which read, 'Made of Styron, A Dow Plastic.' These labels were supplied to him by Dow without cost. The Dow name was well known, and hence the Styron label would help to sell end products which had been made form Styron. Dow promoted the Styron name extensively at the consumer level through national advertising media."

[32] During the development of fiberglass-reinforced piping, one company asked for assistance by Owens-Cornings technicians, but refused to grant these technicians access to the production plant, presumably to prevent spillovers to other customers of Owens-Corning.

[33] See EPRI Journal, April-May 1989. Electric power utilities in the United States are in most cases regulated monopolies. By pooling resources and conducting R&D through EPRI, they can avoid duplication of research efforts.

[34] The list of R&D projects includes: new battery technologies for the automotive industry, induction heating techniques for metals, dielectric drying of textile products, infrared heating in composite fabrication, heat pump technology. See EPRI (1989).

[35] In the example provided by Leenders and Blenkhorn (1988) the externality benefit is somewhat different: the buyer firm profits from a reduction of factor prices.

Appendix to Chapter II

In this appendix I briefly sketch two models. The first model considers the effect of search activities and provides a possible explanation for a positive correlation between spillover rate and research intensity. The second model studies the tradeoff between incentives to protect knowledge and incentives to create knowledge. Again, a positive correlation between extent of spillovers and R&D intensity is possible.

A.II.1 Assumptions

I simplify the exposition by making the following assumptions:

Assumption 1) Industry structure is given exogenously, i.e. there are N firms in the industry.

Assumption 2) Unit costs c are independent of output.

Assumption 3) Firms have a constant price-cost margin. Accordingly, equilibrium prices p are proportional to unit costs c . Let p=m(p-c).

Let M_i denote firm i's expenditure on productive R&D. P_i denotes firm i's protection efforts, and S_i is the search effort firm i engages in in order to find external knowledge. Note that the firm's total R&D budget is equal to $M_i + P_i + S_i$. Furthermore, let E_i denote firm i's profit gross of R&D expenditures and Π_i the net profits, i.e. $\Pi_i = E_i - (M_i + P_i + S_i)$. Q_i is the quantity produced by firm i. Firm i's R&D intensity Z* is defined as the total R&D budget divided by firm i's sales, i.e.

$$(A1) \qquad Z^* = \frac{M_i + S_i + P_i}{pQ_i} = \frac{M_i + S_i + P_i}{mE_i} \quad .$$

The second equality follows directly from observing that $pQ_i = m(p-c)Q_i = mE_i$. Note that earnings are again a function of the firm's own stock of knowledge and the stock of knowledge its competitors have access to, i.e. $E_i = E_i(z_i, z_{-i})$. The advantage of assuming a constant price-cost margin becomes apparent here, since it allows to work directly with profit functions, rather than specifying the mechanics of innovation at the level of cost or product quality.

A.II.2 Search Efforts

Assume that firm i's stock of knowledge is determined by the relationship

$$z_i = M_i + \gamma_i(S_i)\,\theta \sum_{j \neq i} M_j \quad , \tag{A2}$$

where by assumption $0 \leq \gamma_i \leq 1$, $\gamma_i' > 0$, and $\gamma_i'' < 0$. Note that γ_i is now a function of search efforts S_i . Firms maximize their profit Π_i with respect to M_i and S_i. All firms know θ and the function $\gamma_i(.)$. Firms take the R&D and search efforts of their rivals as given. The first-order conditions are then

$$\frac{\partial E_i}{\partial z_i} + \theta \sum_{j \neq i} \gamma_j(S_j) \frac{\partial E_i}{\partial z_j} = 1 \tag{A3}$$

and

$$\frac{\partial E_i}{\partial z_i} \frac{\partial \gamma_i(.)}{\partial S_i} \theta \sum_{j \neq i} M_j = 1 \quad . \tag{A4}$$

Consider now a symmetric equilibrium such that $z^* = z_i^*$, $M^* = M_i^*$ and $S^* = S_i^*$ $\forall i$. Define the following equilibrium elasticities

$$\alpha_{own} = \frac{\partial E_i}{\partial z_i} \frac{z^*}{E(z^*)} \tag{A5}$$

$$\alpha_{comp} = \frac{\partial E_i}{\partial z_j} \frac{z^*}{E(z^*)} \tag{A6}$$

$$\varepsilon_\gamma = \frac{\partial \gamma(.)}{\partial S_i} \frac{S^*}{\gamma_i(S^*)} \quad . \tag{A7}$$

The elasticity α_{own} is the elasticity of earnings with respect to the firm's own pool of knowledge and assumed to be positive. The second elasticity α_{comp} is the elasticity of the firm's earnings with respect to each competitor's pool of knowledge and negative by assumption. Finally, ε_γ denotes the elasticity of $\gamma(.)$ with respect to the firm's own search efforts S.

Transforming the two first-order conditions into expressions using the elasticities yields

$$\text{(A8)} \qquad \frac{M^*}{E^*} = \frac{\alpha_{own} + \theta(N-1)\gamma(S^*)\,\alpha_{comp}}{1 + \theta(N-1)\gamma(S^*)}$$

and

$$\text{(A9)} \qquad \frac{S^*}{E^*} = \frac{\alpha_{own}\,\varepsilon_\gamma\,\theta(N-1)\gamma(S^*)}{1 + \theta(N-1)\gamma(S^*)} \quad .$$

These equations have to be interpreted with some care since one cannot simply differentiate the expressions with respect to θ. Changes in θ will in general cause a subsequent change in $\gamma(S^*)$ which is possibly negative. However, one can construct cases in which $\gamma(S^*)$ increases with the spillover rate θ. It is also necessary to assume that the elasticities defined above are constant for a given range of spillover rates θ. Note that the ratio M^*/E^* is then unambiguously decreasing in θ if $\gamma(S^*)$ increases in θ. Similarly, it is clear from inspection of (A9) that the ratio S^*/E^* is increasing in this case. Since there are no protection efforts P in this model, the total research intensity Z^* is given by

$$\text{(A10)} \qquad Z^* = \frac{M^* + S^*}{mE^*} = \frac{1}{m}\,\frac{\alpha_{own} + \theta(N-1)\gamma(S^*)(\alpha_{comp} + \alpha_{own}\,\varepsilon_\gamma)}{1 + \theta(N-1)\gamma(S^*)}$$

and a greater spillover rate θ will have a positive effect on total research intensity Z^* if in equilibrium $(\alpha_{comp}/\alpha_{own} + \varepsilon_\gamma) > 1$ and if $\gamma(S^*)$ increases with θ. To see this, simply divide the numerator by α_{own} and note that a ratio $(1+ax)/(1+x)$ is increasing in x if and only if $a>1$. This result can be given a straight-forward intuitive interpretation. If the effect of the own knowledge pool on the firm's profit is sufficiently strong in comparison to the effect of competitors' knowledge and if search is sufficiently effective, then the incentive to search can be large enough to outweigh the disincentive effect of spillovers.

A.II.3 Incentives to Protect vs. Incentives to Create

To my knowledge, there have been no attempts so far to explore the implications of an endogenous specification of the spillover rate itself. The view that the rate of spillovers is exogenously given is of course an abstraction. Relaxing this assumption in a model allows the firm to protect its knowledge using some protection technology that may be more or less effective. Patenting can be interpreted as such a protection effort. Secrecy is another protection mechanism.

Protective behavior can be conceptualized in more than one way. I choose a particularly simple specification first by assuming that the spillover rate θ is not a parameter, but an endogenously determined function of protection efforts. In this conceptualization of protection efforts, firms try to prevent information from reaching the public domain. For example, firms in the tire industry sometimes use codenames for chemical inputs so that even production workers have no knowledge of the exact composition of a product. Hence, the amount of knowledge that is in the public domain is reduced.

The function $\theta_i(P_i)$ is assumed to satisfy the conditions $0 \leq \theta_i(P_i) \leq 1$, $\theta(.)' < 0$, and $\theta(.)'' > 0 \; \forall \; P_i \geq 0$. I also assume that all firms extract all knowledge that is in the public domain without incurring further expenditures ($\gamma=1$).

Let firm i's pool of knowledge be given by

$$z_i = M_i + \sum_{j \neq i} \theta_j(P_j) M_j \tag{A11}$$

Firms maximize their profit Π_i with respect to M_i and P_i. All firms know the spillover rate function $\theta_i(.)$ and take the R&D and protection efforts of their rivals as given. The first-order conditions are then

$$\frac{\partial E_i}{\partial z_i} + \sum_{j \neq i} \theta_i(P_i) \frac{\partial E_i}{\partial z_j} = 1 \tag{A12}$$

and

$$\sum_{j \neq i} \frac{\partial E_i}{\partial z_j} M_i \frac{\partial \theta_i(P_i)}{\partial P_i} \quad . \tag{A13}$$

In a symmetric equilibrium these conditions can again be simplified by expressing them in elasticity form. Define the equilibrium elasticity of spillover rate with respect to protection effort as

$$\text{(A14)} \qquad \varepsilon_\theta = \frac{\partial\theta_i(.)}{\partial P_i} \frac{P^*}{\theta_i(P^*)} \quad .$$

The two first order-conditions can then be written as

$$\text{(A15)} \qquad \frac{M^*}{E^*} = \frac{\alpha_{own} + (N-1)\,\theta(P^*)\,\alpha_{comp}}{1 + (N-1)\,\theta(P^*)}$$

and

$$\text{(A16)} \qquad \frac{P^*}{E^*} = \frac{\varepsilon_\theta\,\alpha_{comp}\,(N-1)\,\theta(P^*)}{1 + (N-1)\theta(P^*)} \quad .$$

Note that

$$\text{(A17)} \qquad \frac{M^* + P^*}{E^*} = \frac{\alpha_{own} + (1+\varepsilon_\theta)\,\alpha_{comp}\,(N-1)\,\theta(P^*)}{1 + (N-1)\theta(P^*)} \quad .$$

Obviously, the observed equilibrium spillover rate $\theta(P^*)$ is now endogenously determined. A greater level of protection effort lowers the equilibrium spillover rate and thus encourages more productive R&D. However, it should be noted that had we used a variable rate of knowledge extraction $\gamma<1$, then total R&D intensity could be positively correlated with γ. The reasoning is simply that greater values of γ enhance the disincentive effect from spillovers and lower the ratio M^*/E^*, but they may also trigger protection efforts that are strong enough to outweigh the disincentive effect.

There is a second and more interesting way to conceptualize protection efforts in R&D. It is often very difficult for firms to prevent their own R&D results from spilling over into the public domain. Product innovations are a clear example for this case. The innovator who sells a product in the market cannot distinguish between a friendly buyer and the agent of a competitor wanting to buy the product for purposes of reverse-engineering. However, firms can try to make the reverse-engineering process more costly for their competitors. In the chemical industry, for example, firms may add functionally irrelevant chemical components to a product in order to increase a competitor's costs for a spectral analysis.

To model this behavior, assume that an exogenously given proportion θ of each firm's technical knowledge is in the public domain, but only in embodied form. The rate to which any other firm j can "dis-embody" firm i's knowledge is given by γ_{ji} which is a function of firm i's protective efforts $\gamma_{ji} = \gamma_{ji}(P_i)$. Firm i's pool of knowledge is then given by

$$\text{(A18)} \qquad z_i = M_i + \sum_{j \neq i} \gamma_{ij}(P_j)\theta M_j \quad .$$

The function $\gamma_{ij(.)}$ is assumed to satisfy the conditions $0 \leq \gamma_{ji}(.) \leq 1$, $\gamma_{ji}(.)' < 0$, and $\gamma_{ji}(.)'' > 0$. The first-order conditions are given by

$$\text{(A19)} \qquad \frac{\partial E_i}{\partial z_i} + \sum_{j \neq i} \frac{\partial E_i}{\partial z_j} \gamma_{ji}(P_i)\theta \;=\; 1$$

and

$$\text{(A20)} \qquad \sum_{j \neq i} \frac{\partial E_i}{\partial z_j} \, \frac{\partial \, \gamma_{ji}(P_i)}{\partial P_i} \, \theta M_i \;=\; 1 \quad .$$

The equilibrium elasticity of $\gamma_{ji}(.)$ with respect to protection effort P_i is defined as

$$\text{(A21)} \qquad \varphi_\gamma = \frac{\partial \gamma_{ji}(.)}{\partial P_i} \, \frac{P^*}{\gamma_{ji}(P^*)} \quad .$$

The solutions for M*/E* and P*/E* can then be written in elasticity form as

$$\text{(A22)} \qquad \frac{M^*}{E^*} = \frac{\alpha_{own} + (N-1)\,\theta\,\gamma(P^*)\,\alpha_{comp}}{1 + (N-1)\,\theta\,\gamma(P^*)}$$

and

(A23) $$\frac{P^*}{E^*} = \frac{(N-1)\,\theta\,\gamma(P^*)\,\varphi_\gamma\,\alpha_{comp}}{1 + (N-1)\,\theta\,\gamma(P^*)} \quad .$$

As long as the product $\theta\gamma(P^*)$ is nondecreasing if θ is increased (i.e. γ falls at less than a linear rate while θ increases linearly), the ratio P^*/E^* in (A23) will be increasing in θ. Similarly, the ratio M^*/E^* will be decreasing with the spillover rate θ. A measure of total R&D intensity is then given by

(A24) $$\frac{M^* + P^*}{E^*} = \frac{\alpha_{own} + (1+\varphi_\gamma)\,\alpha_{comp}\,(N-1)\,\theta\,\gamma(P^*)}{1 + (N-1)\,\theta\,\gamma(P^*)} \quad .$$

Note that the elasticity φ_γ is negative by definition. If the term $(1+\varphi_\gamma)\alpha_{comp}$ is greater than α_{own}, then the ratio in (A24) may again be increasing with θ. Again, greater spillovers have a negative effect on the firm's incentive to engage in productive R&D, but may induce protection efforts that are extensive enough to outweigh the disincentive effect.

Chapter III

R&D Spillovers and Crowding Out In Vertically Related Industries

III.1. Introduction

The empirical results summarized in the previous chapter clearly demonstrate the importance of intersectoral information flows for conditions of technological change. But the assumption that these flows are purely exogenous in nature is probably one of convenience and should be dropped once one tries to analyze information spillovers at a more detailed level than has been done in most studies. In accordance with the exogeneity assumption, many researchers have conceptualized information flows as involuntary "leaking" of technology. But as I pointed out above, the empirical studies summarized above cannot distinguish between voluntary or involuntary information dissemination. Spillovers as they have been treated in the empirical literature encompass both types. The last section of chapter II also provided several examples in which firms in one sector of the economy tried to affect the structure of vertically related sectors. The generation of spillover information is one strategic instrument to influence entry conditions in other sectors, and this phenomenon is analyzed formally in this chapter.

I consider the effect of interindustry spillovers on industry structure and R&D incentives in a static model with free-entry as developed by Dasgupta and Stiglitz (1980). The presence of spillovers has important implications if industry structure is determined endogenously. Firms may be able to use spillover knowledge as a substitute for their own R&D efforts. Interindustry spillovers can therefore lead to a reduction of equilibrium sunk cost investments. The number of firms sustainable in a free-entry equilibrium may increase then with the extent of the information externality.

The central point of this chapter is the strategic use of spillover information. Due to their effect on industry structure, interindustry spillovers may lend themselves to be employed as a strategic instrument. Supplier firms can influence the industry structure of a buyer sector in their favor by providing cost-reducing R&D as a public good. Though the market for the technological information breaks down completely, supplier firms can use an indirect appropriation mechanism in order to recoup their R&D investments. The overall extent of interindustry spillovers in this model is then endogenous and depends on technology and demand conditions. Industry structure and R&D incentives in the downstream industry are affected by the supplier's strategic investment in R&D. In essence, when several sectors are considered in conjunction additional R&D incentives arise that have found little attention so far and cannot be described in one-sector models. Describing the conditions under which firms would want to produce spillover information intentionally may therefore help to shed more light on the determination of R&D incentives, both in the spillover producing and the spillover receiving sector.

I also derive several other results of interest for the theory of R&D incentives. For example, the model demonstrates the implications of different spillover specifications in empirical models. If interindustry spillovers are modelled as pure complements of the firm's private R&D efforts, but are in effect substitutes, then the estimated elasticity of production cost with respect to R&D can be biased downwards. As a consequence, the respective industry would appear to have low technological opportunities while it is only taking advantage of the availability of public goods information.

To develop these points in more detail, this chapter proceeds in five sections. In section 2, I briefly revisit some of the results developed by Dasgupta and Stiglitz (1980) in order to describe the benchmark case without spillovers. Section 3 then extends their model by analyzing the effect of interindustry spillover information that substitutes for the firms' own R&D efforts. I derive the implications of these spillovers for industry structure and R&D incentives. Section 4 extends the model to a two-sector model in which a downstream industry receives an intermediate good from a monopolist supplier. I derive conditions under which voluntary transfer of cost-reducing know-how from the supplier to the downstream industry will occur. The results suggest that the supplier will have incentives to provide cost-reducing know-how as a public good if the elasticity of cost with respect to R&D in the downstream industry is relatively small, if demand is relatively inelastic, and if the efficiency of information transfer from the supplier to the downstream industry is sufficiently high. Under these conditions, the supplier's R&D investment has a relatively strong effect on downstream industry structure and the degree of competition among firms, so that the spilling over of information is particularly attractive for the supplier. Finally, section 5 of this chapter presents a discussion of the results and several proposals for future modelling efforts.

III.2 The Basic Model Without Spillovers

The point of departure for this chapter is a model developed by Dasgupta and Stiglitz (1980). In the Dasgupta-Stiglitz model, firms can reduce their cost of production by making R&D investments x. Unit production costs are a deterministic function of these R&D investments, i.e. $c = c(x)$ where $c'(x)<0$ and $c''(x)>0$.[1] Firms entertain Cournot conjectures with respect to their choices of output and R&D expenditures and choose both simultaneously. There is free entry into the industry. Firms enter as long as the endogenously determined R&D expenditures can be covered by the difference between revenues and production costs. Let n indicate the number of firms and Q_i denote the output of the *i*th firm ($i = 1, 2, \dots, n$). Then

$$\{n^*, (Q_1^*, x_1^*), \dots, (Q_i^*, x_i^*), \dots, (Q^*_{n^*}, x^*_{n^*})\}$$

is a free-entry equilibrium if, for $i = 1, 2, \dots, n^*$

$$(1) \qquad [p(\sum_{j\neq i} Q_j^* + Q_i^*) - c(x_i^*)]Q_i^* - x_i^* \geq [p(\sum_{j\neq i} Q_j^* + Q_i) - c(x_i)]Q_i - x_i$$

$$\forall\, x_i, Q_i \geq 0$$

and

$$(2) \qquad [p(\sum_{i=1}^{n^*} Q_i^* + Q) - c(x)]Q - x \leq 0 \quad \forall\, x, Q \geq 0 \ .$$

Firm i maximizes its profits by choosing x_i and Q_i according to

$$(3) \qquad \mathrm{MAX}_{\{x_i, Q_i\}} [p(\sum_{j\neq i} Q_j + Q_i) - c(x_i)]Q_i - x_i \ .$$

Symmetric equilibria[2] are then characterized by the first-order conditions:

$$(4)\qquad p(Q^*)[1-\frac{\eta(Q^*)}{n}] = c(x^*)$$

and

$$(5)\qquad -c'(x^*)\,\frac{Q^*}{n} = 1\ ,$$

where $\eta(Q) = p'(Q)Q/p$ is the elasticity of demand at output level Q. Furthermore, the equilibrium number of firms n^* is determined via the zero-profit condition[3]

$$(6)\qquad [p(Q^*) - c(x^*)]Q^* \geq n^*x^*\ .$$

If profits are negligibly small, then condition (6) holds approximately with equality. To obtain closed-form solutions for x^*, n^*, and Q^* Dasgupta and Stiglitz use specific functional forms for demand and cost functions. In particular, it is presumed that the gross social benefit from consuming Q is given by u(Q)

$$(7)\qquad u(Q) = \frac{\sigma Q^{1-\varepsilon}}{1-\varepsilon}\qquad (\sigma, \varepsilon > 0)\ .$$

The inverse demand function $p(Q) = u'(Q)$ is then given by

$$(8)\qquad p(Q)=\sigma Q^{-\varepsilon}\ .$$

The relationship between production costs and R&D effort is defined by

$$(9)\qquad c(x)=\beta x^{-\alpha}.$$

ε^{-1} is the elasticity of demand and α is the elasticity of marginal cost with respect to R&D and σ is a parameter indicating the size of the market. β is a scaling factor that will allow us to model the cost relationship in more detail.

Solving for x^* and Q^* and using assumptions (8) and (9) Dasgupta and Stiglitz find that

$$(10) \quad x^* = [\sigma(\alpha/n^*)^{\varepsilon}\, \beta^{\varepsilon-1}(1-\varepsilon/n^*)]^{1/[\varepsilon-\alpha(1-\varepsilon)]}$$

and

$$(11) \quad Q^* = (n^*/\alpha\beta)\, x^{*(1+\alpha)} = (n^*/\alpha\beta)\, [\sigma(\alpha/n^*)^{\varepsilon}\, \beta^{\varepsilon-1}(1-\varepsilon/n^*)]^{(1+\alpha)/[\varepsilon-\alpha(1-\varepsilon)]} .$$

Condition (6) can be used to obtain the equilibrium number of firms with free entry

$$(12) \quad n^* = \varepsilon(1+\alpha)/\alpha \ .$$

For (10), (11), and (12) to characterize an equilibrium we have to suppose that $\varepsilon>\alpha(1-\varepsilon)$. Inserting result (12) into equation (10) and (11), one obtains the equilibrium choices for R&D expenditures and output in the free entry case as a function of the underlying parameters α, ε, σ, and β.[4]

It is evident from these results then that industry structure and R&D are determined endogenously. As Dasgupta and Stiglitz point out, the number of firms in the industry is not a measure of the degree of competition since such an economy is always competitive in the sense that entry drives profits down to zero. The equilibrium concept is well-known from models of monopolistic competition (Salop 1979). The costs of R&D can be interpreted as a cost of entry that restricts the maximum number of firms sustainable in equilibrium. Market price $p(Q^*)$ will not be equal to marginal costs since the revenues in excess of production costs cover the fixed costs of R&D. Note also that a higher level of production cost β will tend to reduce R&D expenditures provided that $\varepsilon<1$.[5] This will have an important implication for the pricing policy of supplier firms who can influence R&D efforts in a downstream industry by their choice of factor prices.

For the free entry case Dasgupta and Stiglitz derive an explicit relationship between the R&D intensity Z^* of the industry, the inverse of the elasticity of demand $\varepsilon(Q^*)$ and the equilibrium number of firms:

$$(13) \quad \frac{1}{n^*} = \frac{Z^*}{\varepsilon(Q^*)}$$

where $Z^* = n^*x^*/p(Q^*)Q^*$. This relationship is independent of how firms choose their R&D expenditures, i.e. of equation (5). Taking the presumed R&D behavior into account one obtains

$$(14) \quad Z^* = \frac{n^*x^*}{p(Q^*)Q^*} = \frac{\alpha}{1+\alpha} .$$

Equation (14) states that the industry's R&D intensity will be a function of the elasticity of cost with respect to R&D.[6] This relationship has become an important foundation of empirical studies. It states that the R&D intensity of an industry with free entry and the assumed Cournot posture will be a function of measures of "technological opportunity". This view amends an earlier school of thought in which industry structure was supposed to have some causal relationship with the measure of R&D intensity. It is a rather uncontroversial empirical finding that the effect of measures of concentration in regression studies is weaker, the more control variables for "technological opportunities" are introduced.[7] It should be noted, however, that the Dasgupta-Stiglitz model for economies with free entry makes some very strong assumptions regarding the determination of industry structure. It considers only R&D expenditures as a sunk cost, while it is conceivable that other (and large) expenditures have sunk cost character, too (e.g. selling and advertising expenditures, set-up costs of production, etc.). The effect of R&D expenditures on industry structure is then no longer as pronounced as it is in the Dasgupta-Stiglitz model, and for some industries it may be appropriate to treat industry structure as exogenously given.[8]

III.3 The Effect of Interindustry Spillovers on R&D Incentives and Industry Structure

Dasgupta and Stiglitz confine their analysis to circumstances where only information generated within the firm contributes to cost reduction. This assumption is motivated by the observation that markets for nonembodied technological information often fail to work properly (Arrow 1962). Presumably, a hypothetical seller of technological information has better information about the value of the technology than has the prospective buyer.[9] This basic asymmetry can be resolved through inspection of the information quality by the buyer, but inspection itself would reveal the information to the buyer. Essentially, the market for information breaks down and firms have to rely on their own (and unfortunately duplicative) efforts to reduce their production costs.

If externally produced knowledge is available as a public good to firms in the Dasgupta-Stiglitz model, firms' R&D investments and the equilibrium number of firms will be affected in some way. These changes depend primarily on the character of the external knowledge, and in particular on whether the spillover information is a complement to or substitute for internally generated know-how. External knowledge from other sectors has sometimes been seen as complementing the know-how produced within an industry, thereby enhancing the productivity of R&D. However, it is by no means clear that this is the only or even the dominant effect of interindustry spillovers. The empirical results obtained by Bernstein (1988; 1988) and Bernstein and Nadiri (1988) suggest that interindustry spillovers may be better characterized as substitutes for industry R&D. Based on this empirical evidence, I will assume throughout this chapter that externally produced knowledge is a substitute for private R&D results. This assumption is not in conflict with the Cohen and Levinthal (1989) results discussed in the previous chapter. The model developed here will analyze the incentives of suppliers to provide information which according to Cohen-Levinthal tends to be rather targeted. Downstream firms will not have to increase their absorptive capacity to capture these spillovers.

As Cohen and Levinthal (1989) have noted, external knowledge that substitutes for internally generated know-how can lead to diminished industry R&D efforts if the spillover knowledge is relatively targeted to the receiver's needs.[10] To analyze the implications of such interindustry spillovers, I will assume that the relationship between unit costs and R&D investment is given by

$$(15) \quad c(x,y)=\beta(x+\gamma y)^{-\alpha}$$

where β is a scaling factor, x is the firm's research effort, and γy is the external information captured by the firm. To facilitate the analysis I treat x and y simply as measures of knowledge. Each R&D dollar yields one unit of cost-reducing information. The reader should think of y as the research investment of some external source of information. Sections 4 and 5 of this chapter will elaborate on the origins of this information. The parameter γ maps the cost of acquiring the knowledge y into its value for the firms capturing the spillover. Two effects may be of particular importance here. First, the information transfer between source and the recipients may be imperfect, i.e. $0 \leq \gamma \leq 1$. In this case, the R&D expenditures y are greater than the value of the information γy for the recipient. Second, the production of the spillover knowledge y may be subject to economies of scale or scope. For example, the producer of a new material may be able to apply knowledge gained in the development of the material to the design of products using the material. In this case the spillover producer pays less than one R&D dollar per unit of knowledge such that γ could conceivably be greater than unity.[11]

The most important implication of the cost specification in equation (15) is that the equilibrium structure of the downstream industry (i.e. the number of downstream firms) is partially determined by R&D investments made in the sector in which the spillover knowledge originates. Since spillovers will lower the entry barriers from R&D, more firms can enter the industry. Allowing for this kind of interaction can lead to large deviations from the equilibrium number of firms predicted by the Dasgupta-Stiglitz model.

To demonstrate this result, I assume that firms take γy as given and choose their R&D and output levels simultaneously according to Cournot conjectures. Let N indicate the number of downstream firms (in order to distinguish these results from the Dasgupta-Stiglitz model where the number of firms is given by n). From the first-order conditions for profit-maximizing downstream firms we obtain now:

$$(16) \qquad x^* = [\sigma(\alpha/N)^{\varepsilon}\beta^{\varepsilon-1}(1-\varepsilon/N)]^{1/[\varepsilon-\alpha(1-\varepsilon)]} - \gamma y \quad .$$

To facilitate the analysis let ϕ be defined as the fraction of total cost-reducing know-how provided by external sources via some spillover mechanism, i.e. $\phi = \gamma y/(x^*+\gamma y)$ is the spillover contribution to cost reduction. Then we can rewrite equation (16) as

$$(16') \quad x^* = (1-\phi)\,[\sigma(\alpha/N)^{\varepsilon}\beta^{\varepsilon-1}(1-\varepsilon/N)]^{1/[\varepsilon-\alpha(1-\varepsilon)]}\ .$$

Industry output is given by

$$(17) \quad Q^* = (N/\alpha\beta)\,(x^*+\gamma y)^{1+\alpha} = (N/\alpha\beta)\,[\sigma(\alpha/N)^{\varepsilon}\beta^{\varepsilon-1}(1-\varepsilon/N)]^{(1+\alpha)/[\varepsilon-\alpha(1-\varepsilon)]}\ .$$

In the following sections I assume that x^* is always greater than zero. This assumption can be justified as an implication of adoption costs: the use of external knowledge always requires some (small) private effort to adopt the spillover information. In other words, public goods technology is assumed to be never a complete substitute for all private R&D.[12]

Consider first the case when the number of firms N is given exogenously. From inspection of equation (16) it is clear that the sum of internal and external R&D resources employed for cost reduction purposes is the same as in the Dasgupta-Stiglitz model. Firms take the captured information γy as given and invest up to the point where net marginal benefits from R&D are exhausted. The levels of output and production cost are then unaffected by the spillover phenomenon, but welfare is increased since firms engage in wasteful duplication to a lesser degree. Obviously we have to assume that the production of the public goods R&D requires fewer resources than the duplicative efforts of N firms.

Result 1: If the number of firms N is determined exogenously (e.g. by barriers to entry), interindustry spillovers will reduce each firm's equilibrium R&D investment while the levels of industry output and production cost are the same as without spillovers.

This result owes much to the assumption that private R&D knowledge x and the captured spillover information γy are perfect substitutes. If the external knowledge were perfectly complementary then greater interindustry spillovers would have a stimulating effect on private R&D investments.[13]

Let x^{**} denote the firm's R&D effort if no spillovers are present. With barriers to entry, total R&D expenditures in an industry with $N=\underline{n}$ firms will be equal to $\underline{n}x^* = \underline{n}x^{**} - \phi\underline{n}x^{**} = (1-\phi)\underline{n}x^{**}$. Since price and output are not affected by spillovers, one can conclude that in an industry with barriers to entry and spillovers ϕ, the R&D intensity will be equal to $(1-\phi)$ times the R&D intensity of a corresponding industry[14] with no spillovers.

In a free-entry equilibrium the equilibrium number of firms N^* is affected by the extent of interindustry spillovers since barriers to entry are lower in this case. From the zero-profit condition

$$(18) \quad (p(Q^*) - c(x^*,y))\, Q^* = N^*x^*$$

we obtain by using the results (16) and (17) the equilibrium number of firms as a function of ε, α, and ϕ.

Result 2: In a free entry equilibrium with interindustry spillovers the equilibrium number of firms N^* is given by

(19)
$$N^* = \frac{\varepsilon}{\alpha}\left(\frac{x^* + \gamma y}{x^*} + \alpha\right) = \frac{\varepsilon}{\alpha}\left(\frac{1}{1-\phi} + \alpha\right)$$
$$= \frac{\varepsilon}{\alpha(1-\phi)}(1 + \alpha(1-\phi))$$

where ϕ is defined as the fraction of total cost-reducing know-how provided by external sources via some spillover mechanism, i.e. $\phi = \gamma y/(x^* + \gamma y)$.

This result obviously simplifies to the Dasgupta-Stiglitz result in equation (12) if either γ or y are equal to zero (i.e. $\phi = 0$). Note that the effect of spillovers on industry structure is potentially large. For example, if the value of external information equals private R&D efforts (i.e. $\phi = .5$) then the equilibrium number of firms is approximately twice as large as n^*, the solution obtained in the Dasgupta-Stiglitz model.

We can now use equations (15), (16), (17) and (19) to obtain the research intensity of the industry.

<u>Result 3:</u> In a free entry equilibrium with interindustry spillovers contributing a fraction ϕ of total cost-reducing know-how the research intensity Z^* is given by

(20)
$$Z^* = \frac{N^* x^*}{p(Q^*)Q^*} = \frac{\alpha(1-\phi)}{1 + \alpha(1-\phi)}$$

and an empirically useful transformation is given by

(20')
$$\frac{Z^*}{1 - Z^*} = \alpha(1-\phi) \quad .$$

It is also simple to show that a free-entry industry with spillovers ϕ has a research intensity of $(1-\phi)/(1+\phi)$ times the research intensity of a corresponding industry without spillovers. In comparison to the case with barriers to entry, one can see that free entry leads to a further reduction in the industry's R&D intensity. The result in equation (20) again simplifies to the corresponding equation (14) if ϕ is equal to zero. But if this assumption is violated then it is no longer warranted to derive the measure of technological opportunities α from the research intensity of the industry without correcting for spillover contributions.

To see how estimation biases can arise in this context, assume that data on process R&D expenditures are available and that industries differ with respect to the observed interindustry spillover contribution ϕ that they receive. A theoretical model may specify the elasticity of cost with respect to R&D as an additive function of exogenous variables and the spillover contribution ϕ, i.e. $\alpha = \alpha(\phi, \dots)$ and then estimate equation (14) by regressing R&D intensity on the determinants of the function $\alpha(.)$. If the spillover rate ϕ has a negative effect on R&D intensity (as the above results suggest), then the estimated coefficient of ϕ will be negative. As a consequence, the computed estimates of α will be smaller the greater the spillover contribution is although the R&D elasticity α is not affected by the spillover contribution. Conversely, the correctly specified model would use equation (20) to regress R&D intensity on $\alpha(.)(1-\phi)$. This nonlinear specification would imply no downward bias in the measurement of α. Estimating R&D elasticities from buyer R&D expenditures without correctly specifying the effect of interindustry spillovers may therefore lead to biased results.

It is interesting that empirical investigations based on the complementarity assumption have produced surprisingly small estimates for the R&D elasticities of cost and product quality in some industries. For example, Levin and Reiss (1988, p. 554) note that their estimates of these elasticities appear to be too low in the case of the plastics products industries. As was pointed out in the previous chapter, the available evidence from case studies suggests that suppliers of plastics materials have engaged in considerable R&D efforts to provide process and product design know-how to their buyers. It is conceivable that the low R&D elasticity estimates obtained by Levin and Reiss arise because spillover information is a substitute for industry R&D in this case.

Given the above results, one may be tempted to conclude that the aggregate statistics of an industry with cost elasticity $\alpha(1-\phi)$ and no interindustry spillovers are identical to those of an industry with cost elasticity α and spillovers characterized by ϕ. That would justify the treatment of $\alpha(1-\phi)$ as a measure of the technological opportunities as *perceived* by the industry. Indeed, as equations (19) and (20) indicate, the number of firms in a free-entry equilibrium and the industry's R&D intensity are the same in these two cases. But one can easily see from equation (17) that industry output and production cost are also a function of the *true* parameter α.

Result 4: An industry with R&D elasticity of costs α $(1-\phi)$ and no interindustry spillovers and an industry with R&D elasticity of costs α and spillover contributions ϕ produce at different output and cost levels *although* the equilibrium number of firms and the R&D intensity Z^* are the same in both cases.

These two hypothetical industries may therefore be very different in terms of their information sources and behavior. Furthermore, to treat the estimated value of $\alpha(1-\phi)$ as a measure of technological opportunity may lead to false public policy conclusions. A policy-maker should clearly take α as the relevant measure of technological opportunities - public policy efforts to reduce production costs beyond the level chosen in equilibrium would be affected by the true elasticity α and therefore have a higher return than under the alternative view.

These results also have some implications for the concept of "technological opportunities" in its empirical application as an exogenous industry-level construct. While there is no universally agreed-upon definition of the concept, it is often taken to represent "(...) how costly it is for the firm to achieve some normalized unit of technical advance in a given industry " (Cohen and Levinthal 1989, p. 139). Given that firms outside a given industry may have an incentive to strategically influence technological opportunities (e.g. via intentionally produced information spillovers), it is hard to see how this construct can be completely exogenous in nature.

Consider for example the case of capital equipment producers.[15] Equation (10) suggests that their R&D investments are likely to be influenced by prevailing demand conditions for their products. According to the common conceptualization of technological opportunities (Cohen and Levin 1989, p. 1083), these investments are reflected in the quality of the capital goods and will affect the technological opportunities experienced by the users of the machinery. Downstream technological opportunity itself is supposed to be a major determinant of industry output, and therefore of upstream demand conditions. Thus, technological opportunities will be endogenously determined. This argument suggests that the relationship between industry structure and R&D incentives is not the only one that should be scrutinized for possible endogeneities. However, the problem of endogenously determined technological opportunities can no longer be analyzed in simple one-sector models.[16]

III.4 Supplier Incentives for R&D - The Case of Factor-Neutral Cost Reduction

In this section I extend the simple one-sector model and introduce a supplier monopolist who may profit from enhanced competition in the buyer industry modelled so far. In such a case, incentives for the production of spillovers exist and the extent of spillovers will be endogenous.

To see this consider the following two-sector model. The profits of a monopolist in the upstream sector are affected by the extent of innovation and competition among firms in the downstream industry, for example through the demand for the factor of production that the monopolist sells to downstream firms. The assumption of an upstream monopoly facilitates the discussion, but the analysis can be extended easily to oligopolistic supply sectors. Without spillover production by the upstream firm, the downstream industry will be characterized by the free-entry equilibrium described in section III.2. This equilibrium implies a certain trade-off between the degree of innovation and the degree of competition which may or may not be optimal for the upstream supplier. On the one hand, the supplier likes more competition in the downstream industry, since a greater number of downstream firms will drive prices closer to marginal cost and enhance the supplier's factor demand. On the other hand, the supplier likes the downstream firms to invest in R&D in order to sell greater quantities, and thus have a positive effect on factor demand.

By making the R&D investment y, the monopolist can produce spillover information that will have two effects on the downstream industry. First, by reducing the R&D investments downstream firms are making, the barriers to entry are lowered, more firms can enter the industry, and competition will be more vigorous. Second, the incentives for each firm to undertake its own R&D efforts will be reduced due to enhanced competition. The monopolist will then choose y such as to maximize its profits, i.e. it will try to define the optimal tradeoff between innovation and competition in the downstream industry.

To analyze this tradeoff and the decision of the spillover producer in more detail, it is necessary to make some assumptions regarding the nature of innovation. I extend the Dasgupta-Stiglitz model by introducing an upstream sector which supplies the downstream firms with some factor of production. Maintaining the long-term perspective implicit in the previous assumptions, substitutability of factors should not be excluded ex ante and I will derive results for general cost functions.[17] I further assume that the upstream supplier can only charge linear prices for its commodity and that vertical integration is not feasible. These assumptions and their implications are discussed in the concluding section 5.

For mathematical convenience I assume that the downstream firms produce according to some production function $f(z_1,z_2) = x^{\alpha} g(z_1, z_2)$ with constant returns to scale. The arguments z_1 and z_2 denote the quantities of two factors of production that are supplied by upstream (supplier) industries. R&D expenditures x increase the productivity of downstream firms, but they do so at a decreasing rate. I assume that z_1 is supplied at constant marginal costs w_1. z_2 is the factor quantity produced by the upstream monopolist. The corresponding specification of the cost function is given by

$$(22) \quad c(w_1,w_2,x) = x^{-\alpha}\,\beta\,(w_1,w_2) \quad .$$

I assume that the function $\beta(.)$ satisfies the standard assumptions, i.e. it is nondecreasing, homogeneous of degree 1, concave and continuous in factor prices (Varian 1984, p. 44). Note that innovation has a factor-neutral cost-reducing effect here, i.e the factor shares are independent of the degree of cost reduction. The factor demand functions corresponding to (22) can be obtained via Shephard's Lemma. In particular, (industry) demand for the second factor of production is given by

$$(23) \quad z_2(w_1,w_2,x) = x^{-\alpha}\,\frac{\partial\beta(.)}{\partial w_2}\,Q^* \,.$$

The extended specification of cost reduction implies two effects on the upstream sector's factor demand. First, the factor requirements per unit of final good are reduced the more R&D is done by downstream firms. But a corresponding scale effect leads to enhanced equilibrium output and therefore greater overall factor demand. It is easy to show that the second effect dominates the first whenever final goods demand is elastic (i.e. $\varepsilon^{-1}>1$), which I will assume throughout the rest of paper. Ceteris paribus, the supplier will therefore always prefer greater levels of downstream R&D effort.

Assume first that there are *no spillovers* so that production costs are only determined by the research expenditures of downstream firms. I will use this assumption to describe a benchmark situation. Production costs are then specified according to equation (22). Using equations (11) and (23) the demand function for the second factor of production can be written as

$$(24) \quad z_2(w_1,w_2,x^*) = x^{*-\alpha} \frac{\partial\beta(.)}{\partial w_2} \frac{n^* x^{*(1+\alpha)}}{\alpha\beta(.)} \quad .$$

By inserting expression (10) for x^* into equation (24) we obtain:

$$(25) \quad z_2(w_1,w_2,x^*) = \frac{n}{\alpha} [\sigma (\frac{\alpha}{n})^{\varepsilon} (1-\varepsilon/n)]^{1/[\varepsilon-\alpha(1-\varepsilon)]} \beta(.)^{-\eta} \frac{\partial\beta(.)}{\partial w_2}$$

where the parameter η in equation (25) is given by

$$(26) \quad \eta = 1 + \frac{1-\varepsilon}{\varepsilon-\alpha(1-\varepsilon)} = \frac{1-\alpha(1-\varepsilon)}{\varepsilon-\alpha(1-\varepsilon)} \quad .$$

Note that in the case of $\alpha=0$ this elasticity is simply equal to the elasticity of demand ε^{-1}. We can now solve the maximization problem faced by the upstream supplier and derive an expression for the supplier's profit, given that downstream firms choose their R&D investments according to the Dasgupta-Stiglitz model. Note that the equilibrium concept used here is that of Stackelberg leadership. The supplier anticipates downstream behavior while downstream firms take factor prices as given. The supplier solves the maximization problem:

$$(27) \quad MAX_{\{w_2\}} [w_2 - c_u] z_2(w_2) \quad .$$

where c_u is the supplier's unit which I assume to be constant. Substituting the expression in equation (25) for $z_2(w_2)$ we can write the first-order condition in the following form:

(28) $$-1 + \frac{w_2 - c_u}{w_2} [\eta \frac{\partial \beta(.)}{\partial w_2} \frac{w_2}{\beta(.)} - \frac{\partial^2 \beta(.)}{\partial w_2^2} w_2 (\frac{\partial \beta(.)}{\partial w_2})^{-1}] = 0 \quad .$$

After defining δ as the expression in square parentheses,

(28') $$\delta \equiv [\eta \frac{\partial \beta(.)}{\partial w_2} \frac{w_2}{\beta(.)} - \frac{\partial^2 \beta(.)}{\partial w_2^2} w_2 (\frac{\partial \beta(.)}{\partial w_2})^{-1}]$$

equation (28) can be rewritten as

(29) $$\frac{w_2 - c_u}{w_2} = 1/\delta \quad .$$

As equation (29) shows, the expression in square brackets in (28) is simply the elasticity of factor demand with respect to factor price. Since $\beta(.)$ is a function of the factor price w_2, this expression may itself be a function of w_2. Note that the elasticity of factor demand δ is already written as a combination of elasticity measures which have a convenient interpretation. Let me define

(30) $$k \equiv \frac{\partial \beta(.)}{\partial w_2} \frac{w_2}{\beta(.)}$$

and note that k is simply the cost share expended on factor 2. The second term in (28') can be shown to be equal to the cross-elasticity κ of unit factor demand with respect to factor price[18]

(31) $$\kappa \equiv - \frac{\partial^2 \beta(.)}{\partial w_2^2} w_2 (\frac{\partial \beta(.)}{\partial w_2})^{-1} \quad .$$

This cross-elasticity κ is a measure of substitutability between factors 1 and 2. By applying equation (31) to a CES production function one can show that κ has a simple relationship to the more commonly used elasticity of substitution μ

(32) $\kappa = (1\text{-}k)\,\mu$.

Summarizing these results we can write the elasticity of demand for factor 2 as

(33) $\delta = k\eta + (1\text{-}k)\,\mu \;=\; k\,\dfrac{1-\alpha\,(1-\varepsilon)}{\varepsilon-\alpha\,(1-\varepsilon)} + (1\text{-}k)\,\mu$.

Previously derived expressions for the elasticity of derived demand (Waterson 1980) are nested within this result, since equation (33) also reflects downstream R&D opportunities. If we simply neglect the possibility of cost reduction and set α equal to zero then we obtain the commonly known form of this relationship, i.e. $\delta = k\varepsilon^{-1} + (1\text{-}k)\mu$.[19]

Since η is strictly increasing in α, equation (33) shows that *a greater elasticity of cost with respect to R&D in the downstream industry (i.e. greater values of α) will lead to a greater elasticity of factor demand for the supply sector*. There is a simple intuitive explanation for this result. I noted already that with elastic demand (i.e. $\varepsilon<1$) downstream firms will invest less in R&D, the higher their unit costs are. The higher the downstream R&D elasticities, the more profitable it will be for the supplier to soften its pricing policy in order to enhance downstream incentives for research and development.[20] This relationship indicates that the monopolist supplier - in order to maximize demand spillovers from downstream innovation - will have to relinquish some of its (static) market power.[21]

To provide an example, consider a Cobb-Douglas production function $f(z_1,z_2) = x^{\alpha}\, z_1{}^{a} z_2{}^{1-a}$ such that $\beta(.)=a^{-a}(1-a)^{a-1}w_1{}^{a}w_2{}^{1-a}$. With simple calculations one can show that δ is independent of w_2 in this case and that

$$(34) \qquad \delta = 1 + \frac{(1-\varepsilon)(1-a)}{\varepsilon - \alpha(1-\varepsilon)} \;.$$

In the extreme case of α converging to zero (i.e. cost reduction in the downstream industry is virtually impossible) the expression for the elasticity of factor demand converges to $\delta' = \varepsilon^{-1}(1\text{-}a) + a$. Given that the factor cost share k is equal to 1-a and that the elasticity of substitution is unity for a Cobb-Douglas production function, this is consistent with Waterson's (1980) result.

Rewriting equation (29), the supplier's profit-maximizing factor price is

$$(35) \qquad w_2{}^* = \frac{c_u}{1 - 1/\delta} \;.$$

Using equations (35) and (25) we can write the monopolist's profit as

$$(36) \qquad \Pi_u(w_2{}^*) = [w_2{}^* - c_u]\, z_2(w_2{}^*)$$

$$= \frac{k}{\delta}\,\beta(.)^{1-\eta}\,\frac{n}{\alpha}\left[\,\left(\frac{\alpha}{n}\right)^{\varepsilon}\sigma(1\text{-}\varepsilon/n)\,\right]^{1/[\varepsilon-\alpha(1-\varepsilon)]}$$

where $\beta(.)$ is evaluated at $w_2{=}w_2{}^*$.

Several comparative statics of the reduced-form supplier profit function (36) deserve to be mentioned. First, if there are negligible opportunities for cost reduction in the downstream industry (α converges to zero), the result in equation (36) simplifies to the supplier profits obtained in a static world without technological progress. Second, as intuition would suggest, the supplier profits are an increasing function within the admissible parameter range of *n*. But differentiating supplier profit in equation (36) with respect to n one can see that n^*, the equilibrium number of downstream firms with free entry, is not optimal from the supplier's perspective. The supplier profit function in equation (36) is single-peaked in n and assumes a maximum at $n_0 = \varepsilon/\{(1-\varepsilon)\alpha\} + \varepsilon$ which is always larger than n^*, the sustainable number of downstream firms in a free-entry equilibrium. This result is independent of the particular form of the downstream production function. The supply sector would therefore prefer to face a greater number of downstream firms than can be sustained in a free-entry equilibrium. Using equation (19), one can show that this optimal number of downstream firms n_0 would be induced by a spillover fraction ϕ that is just equal to ε. Hence, the less elastic demand, the more desirable will be the presence of spillovers from the monopolist's perspective.

To induce a more favorable downstream industry structure, suppliers may attempt to provide the cost-reducing know-how as a public good to the downstream sector. Let me assume now that some cost-reducing know-how for use in the downstream industry can be produced by the upstream monopolist. The relevant cost specification is now

$$(22') \quad c(w_1, w_2, x) = (x+\gamma y)^{-\alpha}\, \beta(w_1, w_2) \ .$$

An important restriction is that downstream firms have to produce some amount of knowledge privately in order to adapt external knowledge to their idiosyncratic production environments. This assumption effectively prevents the monopolist from full quasi-integration, i.e. the monopolist cannot emulate the vertically integrated structure by transforming the downstream industry into a pure production sector with no private R&D. Such a solution may be theoretically appealing, but it appears rather artificial given the well-known observation that technical problem-solving is often of a local and therefore idiosyncratic nature.[22]

Using equation (19) we can define the equilibrium number of downstream firms N as a function of the monopolist's spillover production ϕ

$$(37) \quad N(\phi) = \frac{\varepsilon}{\alpha(1-\phi)}(1 + \alpha(1-\phi)) \quad .$$

The factor demand function (25) can then be written as a function of factor price and spillover contribution ϕ

$$(38) \quad z_2(w_2,N(\phi)) = \frac{N(\phi)}{\alpha}\left[\sigma\left(\frac{\alpha}{N(\phi)}\right)^{\varepsilon}(1-\varepsilon/N(\phi))\right]^{1/[\varepsilon-\alpha(1-\varepsilon)]}\beta(.)^{-\eta}\frac{\partial\beta(.)}{\partial w_2}$$

$$\equiv \frac{N(\phi)}{\alpha}\ A(N(\phi))\ \beta(.)^{-\eta}\frac{\partial\beta(.)}{\partial w_2} \quad .$$

One can see from equations (37) and (38) that both $N(\phi)$ and $z_2(w_2,N(\phi))$ are continuous and twice continuously differentiable in ϕ over $0 \leq \phi < 1$. Let $R(w_2,N(\phi))$ denote the sum of upstream and downstream R&D expenditures as a function of ϕ and w_2

$$(39) \quad R(w_2,N(\phi)) = [\sigma(\alpha/N(\phi))^{\varepsilon}(1-\varepsilon/N(\phi))]^{1/[\varepsilon-\alpha(1-\varepsilon)]}\beta(.)^{1-\eta}$$

$$= A(N(\phi))\ \beta(.)^{1-\eta} \quad .$$

$R(.)$ is continuous and continuously differentiable in w_2 and ϕ. The cost of the upstream firm's research effort necessary to produce the fraction ϕ of total cost-reducing know-how $R(.)$ is given by $(\phi/\gamma)R(.)$. Note that for admissible values of ϕ the value of $N(\phi)$ is always greater or equal to n^* (the equilibrium number of firms in the Dasgupta-Stiglitz model).

The supplier anticipates downstream behavior and chooses its research contribution ϕ and factor price w_2. Given the solutions x^*, Q^* and N as a function of ϕ and w_2, the suppliers' maximization problem can be written as

$$(40) \quad \mathrm{MAX}_{\{w_2,\phi\}}\,(w_2 - c_u)\, z_2(w_2,N(\phi)) \;-\frac{\phi}{\gamma}\, R(w_2,N(\phi))$$

or by making use of the definitions in expressions (38) and (39) as

$$(41) \quad \mathrm{MAX}_{\{w_2,\phi\}}\,(w_2 - c_u)\frac{N(\phi)}{\alpha}\; A(N(\phi))\;\; \beta(.)^{-\eta}\frac{\partial\beta(.)}{\partial w_2} \;-\frac{\phi}{\gamma}\, A(N(\phi))\;\; \beta(.)^{1-\eta} \quad .$$

The two first-order conditions can then be written in simplified form as

$$(42) \quad A(N(\phi))\frac{\partial}{\partial w_2}[\,(w_2\text{-}c)\frac{N(\phi)}{\alpha}\,\beta(.)^{-\eta}\frac{\partial\beta(.)}{\partial w_2} \;-\; \frac{\phi}{\gamma}\,\beta(.)^{1-\eta}] \;=\; 0$$

and

$$(43) \quad \beta(.)^{1-\eta}\;\frac{\partial}{\partial\phi}[\,\frac{w_2\text{-}c}{w_2}\,k\,\frac{N(\phi)}{\alpha}\,A(N(\phi)) \;-\; \frac{\phi}{\gamma}\,A(N(\phi))\,] \;=\; 0 \quad .$$

From the first first-order condition we obtain again

$$(44) \quad \frac{w_2^*\text{-}c}{w_2^*} \;=\; \frac{1}{\delta}[1 - \frac{\phi}{\gamma}(1\text{-}\eta)\frac{\alpha}{N(\phi)}] \;\equiv\; \frac{1}{\delta^*} \quad ,$$

where δ is defined as in equation (28').

Comparing result (44) to the one in (29) one can see that the dependence of total R&D expenditures R(.) on the factor price introduces a second-order effect here, captured by the last term in square parentheses. Note that for $N=n^*$ (no spillover production, i.e. $\phi=0$) this second-order term is zero so that result (29) is nested within result (44).

The second first-order condition corresponding to the maximization problem in (43) is

$$(45) \quad \frac{\partial \Pi_u}{\partial \phi} = \beta^{1-\eta} A(N(\phi)) \frac{\partial N(\phi)}{\partial \phi} \Big[\frac{k}{\alpha \delta^*} \Big[1 + \frac{\varepsilon}{\varepsilon - \alpha(1-\varepsilon)} \Big[\frac{1}{N(\phi)-\varepsilon} - 1 \Big] \Big] - \\ - \frac{1}{\gamma} \frac{\alpha(N(\phi)-\varepsilon) - \varepsilon}{\alpha(N(\phi)-\varepsilon)} \frac{\varepsilon}{N(\phi)(\varepsilon - \alpha(1-\varepsilon))} \Big[\frac{1}{N(\phi)-\varepsilon} - 1 \Big] - \frac{1}{\gamma} \frac{\partial \phi}{\partial N} \Big] = 0 \ .$$

Result (45) can be transformed to a cubic equation, the solutions of which are candidates for an interior maximum ϕ^*, but have to be checked with respect to local concavity and compared to the corner solution for $\phi=0$. Particular equilibria can therefore only be determined numerically under suitable parameter assumptions. However, it is possible to establish a simple sufficient condition for the existence of a global profit maximum with $0<\phi<1$.[23]

This condition follows from observing that the derivative in expression (45) is always negative as ϕ approaches 1. Due to the continuity of the profit function and of its first derivative, there must exist a global profit maximum for some $\phi \in (0,1)$ if at $\phi=0$ the derivative of the profit function with respect to ϕ is positive. Evaluating expression (45) at $\phi=0$ (which corresponds to $N=n^*$) and requiring it to be greater than zero we find that supplier involvement in downstream cost reduction will be profitable if

$$(46) \quad \frac{k}{\delta} > \frac{1}{\gamma} \Big[\frac{\alpha}{\varepsilon} + \alpha^2 \Big(\frac{1}{\varepsilon} - \frac{1}{\varepsilon^2} \Big) \Big]$$

or by inserting expression (33) for δ and rearranging terms

(47) $$\gamma > \frac{\alpha}{\varepsilon^2}\eta\,(\eta + \frac{1-k}{k}\mu)\ .$$

The term on the right-hand side of inequality (46) is always positive as long as $0 < \varepsilon < 1$ and $\varepsilon > \alpha(1-\varepsilon)$. These are conditions that were imposed above already. Conditions (46) and (47) have a simple intuitive interpretation. The left-hand side of (46) contains parameters that reflect in some way the dependence of downstream producers on the monopolist's factor of production, such as the elasticity of factor demand and the factor share the supplier provides for downstream production.[24] The condition then spells out that the dependence of downstream producers on the supplier's commodity has to be sufficiently high to create incentives for the kind of supplier involvement discussed here. The critical level is a function of the elasticity of downstream cost with respect to R&D, the inverse of the elasticity of demand, and the efficiency of know-how transfer.

These conditions indicate that the downstream industry may operate in one of two regimes. If the supplier's incentives for the generation of cost-reducing know-how are not sufficiently strong, then the Dasgupta-Stiglitz equilibrium with $N=n^*$ and $\phi=0$ will prevail. However, if increasing the number of downstream competitors conveys a large enough premium on the supplier, then a regime switch will occur. The notion of such a regime switch is appealing because it is consistent with many taxonomic results provided by institutionally oriented researchers. Pavitt (1984), for example, has argued that innovation in different industries can be characterized by a small number of distinct patterns.

Figure III.1 depicts the typical shape of the supplier's profits as a function of γ, the efficiency of know-how transfer, over some range of $N \geq n^*$.[25]

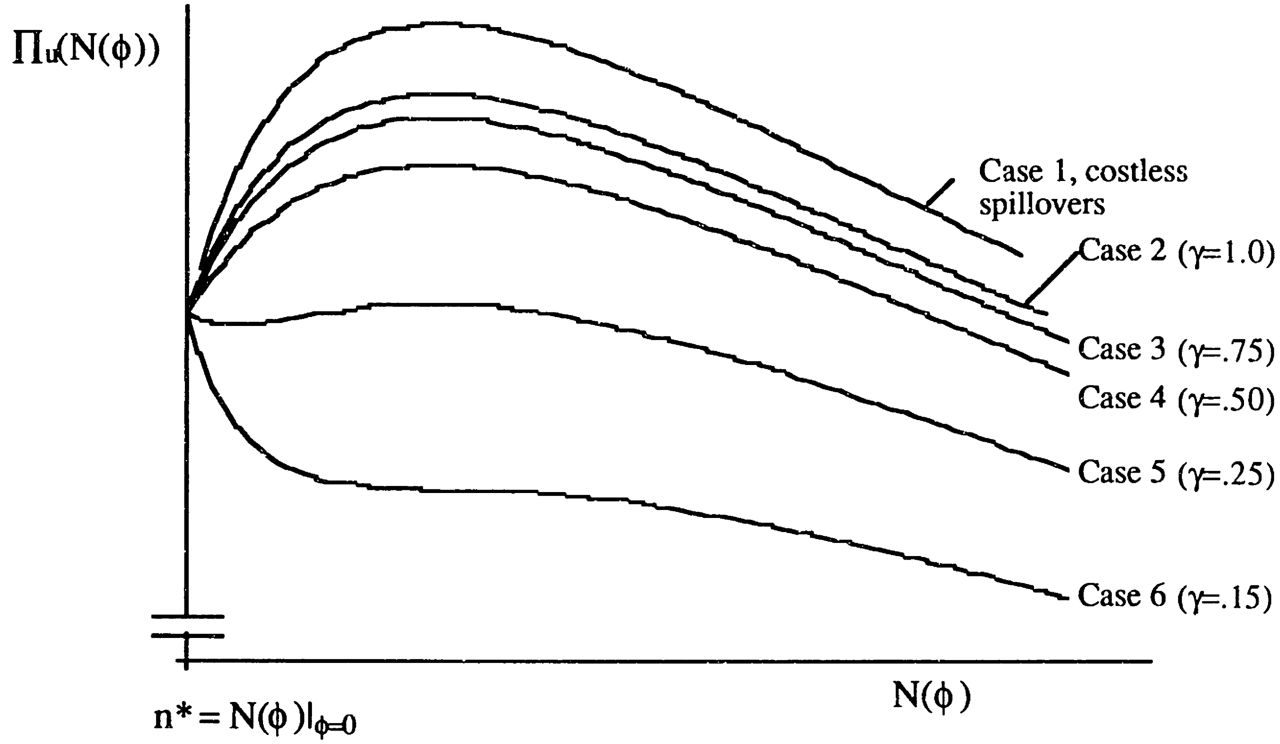

Figure III.1

Supplier Profit Π_u as a Function of γ and $N(\phi)$

Case 1 in figure III.1 represents the supplier's profits as given by equation (36), i.e. with costless spillovers ϕ. This curve attains its maximum at $n_0 = \varepsilon / \{(1-\varepsilon)\alpha\} + \varepsilon$. The other curves represent the supplier's profits (gross of fixed costs) as given by equation (40). The efficiency of know-how transfer is set to γ=1.0 (Case 2 in figure III.1), γ=.75 (Case 3), γ=.5 (Case 4), γ=.25 (Case 5), and γ=.15 (Case 6). Cases 2, 3, 4 satisfy the sufficient condition (46). In case 5, the sufficient condition is not met but a profit maximum with ϕ>0 clearly exists. Finally, in case 6 no such equilibrium exists and the Dasgupta-Stiglitz equilibrium leaves the supplier with the best possible profit rate.

Condition (47) describes the critical level of information transfer efficiency at which a regime switch will occur. Differentiation of the right-hand side of the inequality (47) demonstrates that the critical level of γ is unambiguously increasing in the downstream industry's R&D elasticity α, and decreasing in the elasticity of demand ε^{-1}. Furthermore, greater elasticities of substitution μ will unambiguously increase the required minimum efficiency of information transfer, while an increase in the supplier's cost share k reduces the critical level of γ as long as substitution is feasible. In the case of a Leontief production function ($\mu=0$, i.e. there are no substitution possibilities), the supplier's cost share becomes irrelevant since the input it supplies is crucial for downstream production.

Table III.1 and III.2 present a tabulation of the critical values of γ as a function of the R&D elasticity of cost α and the inverse demand elasticity ε. Table III.1 lists the results of these calculations for the case of downstream production with a Cobb-Douglas function ($\mu=1$) and a cost share k of 0.2. For a regime switch to occur, γ has to exceed the tabulated values. If downstream production occurs in fixed proportions ($\mu=0$) then the critical values of γ (reported in table III.2) are independent of the cost share k. Furthermore, since a case of k=1 is equivalent to the Leontief case, the critical values of γ converge with increasing cost shares k to those in table III.2.

Table III.1

Critical Values of γ - Cobb-Doublas Production Function

Factor Share k = .2

			ε		
α	0.1	0.3	0.5	0.7	0.9
0.01	1.36	0.24	0.12	0.08	0.06
0.03	3.80	0.70	0.35	0.23	0.17
0.05	5.88	1.13	0.58	0.38	0.28
0.07	7.60	1.52	0.79	0.53	0.39
0.09	8.96	1.89	1.00	0.67	0.51
0.11	9.96	2.22	1.20	0.82	0.62
0.13	*	2.52	1.39	0.96	0.73
0.15	*	2.79	1.58	1.09	0.84

* indicates a violation of the condition $\varepsilon > \alpha(1-\varepsilon)$.

Table III.2

Critical Values of γ - Leontief Production Function

			ε		
α	0.1	0.3	0.5	0.7	0.9
0.01	0.99	0.11	0.04	0.02	0.01
0.03	2.92	0.33	0.12	0.06	0.04
0.05	4.78	0.54	0.20	0.10	0.06
0.07	6.56	0.74	0.27	0.14	0.09
0.09	8.27	0.94	0.34	0.18	0.11
0.11	9.91	1.13	0.42	0.22	0.13
0.13	*	1.31	0.49	0.25	0.16
0.15	*	1.49	0.56	0.29	0.18

* indicates a violation of the condition $\varepsilon > \alpha(1-\varepsilon)$.

This analysis of the sufficient condition (46) implies that the monopolist's incentives are particularly strong for small price elasticities of demand and R&D elasticities of production costs. This result can be interpreted intuitively in the following way. The provision of cost-reducing know-how by the supplier has two effects. On the one hand, it increases the degree of competition in the downstream industry, on the other hand, increased competition will lower downstream R&D incentives. If the R&D elasticity α of production costs is high, then the supplier will forego large benefits from cost reduction by reducing downstream R&D incentives. In addition to the foregone benefits from cost reduction, the upstream supplier's R&D efforts are also relatively expensive if α is large. Conversely, greater competition will yield relatively high returns to the supply sector if downstream demand is less elastic. Relatively inelastic market demand will also tend to lower δ, the elasticity of factor demand, while greater cost elasticities α will lead to more elastic factor demand.

This evaluation is of course based on the sufficient condition in (47) and therefore conservative. However, a numerical analysis of the profit maximization problem (41) suggests that the sufficient condition represents a good characterization of the complete set of profit maxima. The set of cases in which the sufficient condition fails and a profit maximum exists is very small. Simulation experiments also demonstrate that the equilibrium supplier contributions ϕ^* are negatively related to the elasticity of demand ε^{-1}. The results from these calculations also suggest that the supplier's return on R&D (defined as the profit gain from spillover production divided by R&D investment) decreases as market demand gets more elastic and as the R&D elasticity α increases.

For specific parameter assumptions[26] I also computed the equilibrium spillover contributions ϕ^* and the transformed R&D intensity $Z^*/(1-Z^*)=\alpha(1-\phi^*)$ as a function of R&D elasticity α and inverse demand elasticity ε. The results are plotted in the appendix in figures A.III.1 to A.III.4. These three-dimensional plots dramatically exemplify the switching property of the computed equilibria. Consider for example the abrupt transition between the two regimes in figure A.III.1. The values for the downstream industry's R&D intensity corresponding to figure A.III.1 are plotted in figure A.III.3. For small values of α and ε, one can observe the linear relationship predicted by the Dasgupta-Stiglitz model, while intentional spillover production by the supplier leads to a diminished R&D intensity for relatively inelastic demand (ε close to 1) and relatively low R&D elasticities α.

The welfare implications of supplier involvement in downstream cost are even more difficult to evaluate than the first-order conditions. Simulation results suggest that cases with both positive and negative welfare implications can be constructed. However, in all cases encountered in the simulation studies, the change in welfare was relatively small (on the order of one per cent or smaller) when compared to the Dasgupta-Stiglitz equilibrium.

III.5 Discussion and Further Research

The results described here exploit the most interesting feature of the Dasgupta-Stiglitz model, namely the tradeoff between (static) competition and R&D incentives. From the supplier's point of view, the tradeoff between competition and innovation in the downstream industry entails too much innovation and too little competition. Using the spillover mechanism the supplier can induce favorable changes in downstream industry structure.

The model demonstrates that the extent of interindustry spillover knowledge may not be exogenous. Quite to the contrary, R&D incentives of firms in different industries interact with each other in this model and spillovers are used for strategic purposes. Furthermore, the supplier's decision to provide technological know-how as a public good avoids the well-known difficulties of selling information in the market place. Instead of charging a price for the information, the supplier receives in return a profit from a demand spillover. No patents or other protective means are necessary for the supplier to appropriate rents from innovation.

One can interpret the supplier's appropriation mechanism as a strategically induced swap of spillover benefits, of course with a net gain for the upstream firm. The supplier's incentives to make use of this mechanism depend on the degree to which the demand spillover is concentrated. An upstream industry with many players has to share the gains from enhanced factor demand and may therefore lack the incentives to provide the free good. "Monopoly power" may therefore indeed be conducive to promote incentives for technological change, though this result should not be interpreted as a classical Schumpeterian hypothesis.

The strategic appropriation mechanism described here is particularly effective if the downstream sector cannot substitute away from the monopolist's commodity input. If good substitutes for the monopolist's commodity are available and if the cost-reducing information can be exploited in conjunction with these substitutes, then the incentives for voluntary spillover production are reduced. However, there may be significant impediments to substitution for a number of reasons. First, the technological possibilities of substituting commodities for each other may be limited. Moroney and Trapani (1981), for example, suggest that the elasticity of substitution for several mineral inputs is significantly lower than unity (the elasticity implied by a Cobb-Douglas specification). Furthermore, it is well-known that relatively small switching costs can confer significant monopoly power on upstream suppliers (Klemperer 1987). I have ruled that out by assuming that the input supplied by the monopolist is a commodity, but the argument made here can also be applied to a local monopolist (or monopolistic competitor) in a horizontally differentiated market. Note also that the marginal benefit to differentiation is enhanced once the indirect appropriation mechanism discussed here is taken into account.

While the above model has focused on cost reductions in the downstream production process, a similar model can be devised with regard to product innovation in the downstream industry. Moreover, the mechanism of appropriating returns to R&D via enhanced demand 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 the basic principle easily to industries with demand complementarities or to monopsonistic sectors who may seek to induce price reductions among their suppliers.

Other applications of this idea may be found in 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. 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.

The above analysis takes as given that vertical integration by the supplier into downstream production is infeasible or not desirable. This assumption has strong implications and the reader deserves some explanations here. Empirically, the assumption seems to be warranted. Case studies in which intentional spillover production has been described (see chapter II) usually portray a strong aversion on the part of materials producers to integrate forward into end product markets. Integration into semi-fabricated products may be common as Stuckey (1983) points out for the case of the aluminum industry, but full vertical integration into the manufacturing of final goods is rare. Corey (1956) and VanderWerf (1990a) also find only isolated cases of vertical integration in their studies.

A theoretical justification of the assumption that vertical integration into downstream production is undesirable for upstream producers is more difficult. Reasonable suggestions are that the entrepreneurial capacity of the upstream firm exhibits diminishing productivity (Friedman 1976, ch. 5), or that the monitoring costs associated with hierarchical organization are substantial (Alchian and Demsetz 1972; Williamson 1975, pp. 115-132). A clear theoretical case against vertical integration into downstream production also exists if additional sunk costs exist that cannot be avoided by integration (e.g. setup costs in spatially differentiated markets).

However, the observation that quasi-integration (Blois 1972) into R&D is apparently desirable while integration into production itself is not raises interesting theoretical issues. The economic literature usually portrays vertical integration in the manufacturing sectors of the economy as an expansion of the boundaries of the firm across all functional areas.[27] The behavior underlying this model suggests that firms may want to expand their boundaries in some areas (like R&D and advertising) while maintaining their original boundaries with respect to manufacturing activities. An explanation of this selective integration behavior will ultimately depend on a better assessment of the costs of integration than is possible to date.[28]

I conclude with some suggestions for future research. In the model presented above incentives of firms in several sectors interact and become determinants of the innovation process observable in one industry. In order to avoid even more complex mathematical derivations, I used convenient, yet plausible assumptions regarding the interaction of private R&D with spillover knowledge. A more general treatment should be attempted in order to check the robustness of the results presented here. Moreover, the above model was essentially static and employed a long-run perspective by assuming free entry and simultaneous moves. An explicit modelling of the time structure of the innovation process would allow one to analyze the short-term gains from supplier involvement in downstream innovation. It should also prove interesting to consider the interaction between vertically related firms in stronger appropriability regimes. Corey (1956) suggests that patent races between suppliers and downstream firms can arise - the supplier may have preemption incentives in order to prevent the emergence of monopoly power (and subsequent double-marginalization) in the downstream industry. Some of these issues are taken up in the next chapter of this thesis.

FOOTNOTES FOR CHAPTER III

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[1] The assumption of a deterministic R&D technology is maintained throughout the chapter.

[2] Dasgupta and Stiglitz (1980) provide (in their Appendix 1) a detailed treatment of conditions for the existence of symmetric equilibria.

[3] See Dasgupta and Stiglitz (1980, p. 276). To simplify the exposition I will neglect the integer problem. This is likely to be a reasonable approximation as long as the number of firms is "large".

[4] Note that results (10) and (11) will also apply to an oligopoly with barriers to entry if one substitutes for n* the exogenously given number of firms, say $\underline{n}$. (In this case $\underline{n}$ must be in the interval [ε,n*].) In the case with barriers to entry industry output increases with the number of firms $\underline{n}$ since greater competition causes a price reduction in this model and thus leads to enhanced consumption. But as Dasgupta and Stiglitz also point out, greater competition does not lead to greater cost-reduction. Unit cost of production will be higher if the number of firms is increased.

[5] Dasgupta and Stiglitz refer to β as a measure of how costly R&D technology is. In this paper, β is used to model in greater detail the determinants of production costs. This means, however, that I will have to make assumptions regarding the nature of cost-reducing innovations, e.g. whether they are factor-neutral or not.

[6] A very similar result can be obtained for a model of product innovation. See Levin and Reiss (1988).

[7] These issues and the concept of technological opportunity are discussed in detail in Cohen and Levin (1989, pp. 1083-1095).

[8] Levin and Reiss (1988) maintain the free-entry assumption but explicitly include sunk costs other than those of R&D in their model. I discuss some of the effects of additional sunk costs in the appendix to this chapter.

[9] The quality of licensed information is analyzed in Rockett (forthcoming). A detailed analysis of imperfections in the market for technology licenses has been provided by Caves et al. (1983). See also von Hippel (1982) for a discussion of appropriability from nonembodied and embodied know-how.

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[10] According to Cohen and Levinthal (1989), suppliers tend to provide relatively targeted information so that the receiving firms may not have to increase their "absorptive capacity".

[11] For a discussion of economies of scale in R&D and the role of firm size see Cohen and Levin (1989, p. 1067).

[12] This assumption follows automatically if we assume that the efficiency of information transfer γ goes to zero as the R&D expenditures of downstream firms go to zero. One can model such relationships explicitly, e.g. by assuming a small imperfection in substitutability as in Levin and Reiss (1988, p. 543). For example, if cost are given by $c(x,y) = x^{-\theta}(x+\gamma y)^{-\alpha}$ then zero private expenditures x imply infinitely high costs as long as $\theta>0$. However, such a specification results in greater mathematical complexity.

[13] For example, if the cost specification were given by $c(x,y) = ((1+y)x)^{-\alpha}$ then downstream firms would spend more on private R&D as spillovers y increase, but the industry's R&D intensity would not be affected, since the elasticity of cost with respect to private R&D x is independent of the spillover level.

[14] The term corresponding industry refers to an industry with the same demand conditions and R&D elasticity of production cost.

[15] Schmookler (1962, p. 212) discusses some of these issues and argues that a lack of innovative performance by suppliers may trigger invention efforts in the buyer sector. Scherer (1982b) presents new empirical evidence regarding this issue.

[16] This argument should be understood as conceptual support for alternative approaches, such as Jaffe's (1986) measure of technological proximity or von Hippel's (1988a) classification of functional relationships. See also the comment by Cohen and Levin (1989, p. 1095) on vertical appropriability.

[17] Substitutability of factors implies a vertical distortion (Tirole 1988, ch. 4). So does of course the existence of sunk costs, since a second price margin is introduced to cover these outlays.

[18] One can simply use the fact that unit factor demand functions are homogeneous of degree zero in factor prices to derive this property. See Varian (1984, p. 71).

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[19] 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).

[20] This result has to be supported by an important assumption. Suppliers act as Stackelberg leaders in this model and *commit* to a factor price that encourages downstream innovation. If such a commitment is not credible then downstream firms would anticipate opportunistic pricing once the innovation has been introduced. Consequently, the ex ante R&D investments by downstream firms would be lower.

[21] This can be given another interpretation. Unless the monopolist wishes to provide all innovations that convey some form of benefit on him through own efforts, he had better not have perfect appropriability. In the extreme case in which a monopolist has the power of perfect price-discrimination the downstream users of its commodity will appropriate no rent from innovation and hence not innovate. All incentives are shifted to the monopolist. The literature on price discrimination has usually pointed out the positive incentive effect for the monopolist but completely neglected the disincentive effect imposed on firms in other sectors.

[22] Rosenberg (1982) and von Hippel (1991) provide detailed discussions of technological idiosyncrasies.

[23] A sufficient condition for $\phi=0$ to be an equilibrium is that the derivative of the profit function be negative for any admissible value of $\phi>0$. In this case the supplier's benefits from increasing the number of downstream firms do not outweigh the costs of providing the necessary cost-reducing knowledge. Additional solutions of the first-order condition emerge when the derivative of Π_u is negative at $\phi=0$, but has a minimum and a maximum for $\phi>0$. (See for example case 5 in figure III.1.) These circumstances prove difficult to evaluate due to the nature of the first-order condition.

[24] Note that the elasticity of factor demand δ is a function of the parameters k, α, and ε. Therefore the factor share and the elasticity of factor demand are not independent of each other if factor prices are determined endogenously.

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[25] The other parameters on which these simulated results are based are: $\mu=1$ (Cobb-Douglas production function), $k=.5$, $\varepsilon=.5$, $\alpha=.05$.

[26] The parameter assumptions are: $\mu=1$ (Cobb-Douglas), $\gamma=1$, $w_1=1$, $c=1$.

[27] An exception from this rule is the strategy literature on joint ventures. For a study of the R&D boundaries of the firm see Pisano (1990).

[28] See Holmstrom and Tirole (1989) for a summary of the arguments, in particular the incomplete contracting framework.

Appendix to Chapter III

In this appendix I shortly state several of the above results for the case of sunk costs other than those of research and development. Since the steps of the derivation are rather simple, I do not reproduce them here. Let the sunk costs (for production setup, advertising, sales services, etc.) be given by S. The firm's maximization problem given in equation (3) then takes the form

$$\text{(3A)} \qquad \mathrm{MAX}_{\{x_i, Q_i\}} \; [p(\sum_{j \neq i} Q_j + Q_i) - c(x_i)]Q_i - x_i \; - S$$

and the free-entry condition becomes

$$\text{(18A)} \qquad (p(Q^*) - c(x^*,y))\, Q^* = N^*(x^*+S) \; .$$

In the presence of upstream spillover contributions ϕ, the equilibrium number of downstream firms $N^*(\phi)$ will then be given by

$$\text{(37A)} \qquad N(\phi) = \frac{1}{(1+S/x^*)} \, \frac{\varepsilon}{\alpha(1-\phi)} + \varepsilon \quad .$$

This equation simplifies to the one given in (37) if S is equal to zero. Note that $N(\phi)$ is decreasing in S as should be expected. It is clear from equation (37A) that the marginal effect of spillover production (i.e. increasing ϕ) on industry structure is the greater the smaller the sunk costs S are.
Finally, we can write the research intensity of the industry Z^* as

$$\text{(20A)} \qquad Z^* = \frac{N^* x^*}{p(Q^*)Q^*} = \frac{\alpha(1-\phi)}{1+\alpha(1-\phi)} \left(1 - \frac{N^* S}{p(Q^*)Q^*}\right)$$

where the last term on the right-hand side is the industry's sunk costs divided by industry sales. For empirical purposes, the following transformation is again convenient:

$$(20A') \qquad \frac{Z^*}{1 - (Z^* + V^*)} = \alpha(1-\phi)$$

where V^* is defined as sunk costs S divided by the firm's sales $p(Q^*)Q_i$. The left-hand side can be interpreted as the dependent variable in a regression analysis if suitable data for sunk costs and R&D intensity are available.

Figure A.III.1

Spillover Contribution $\phi(\alpha,\varepsilon)$

k=.1, Cobb-Douglas Production Function

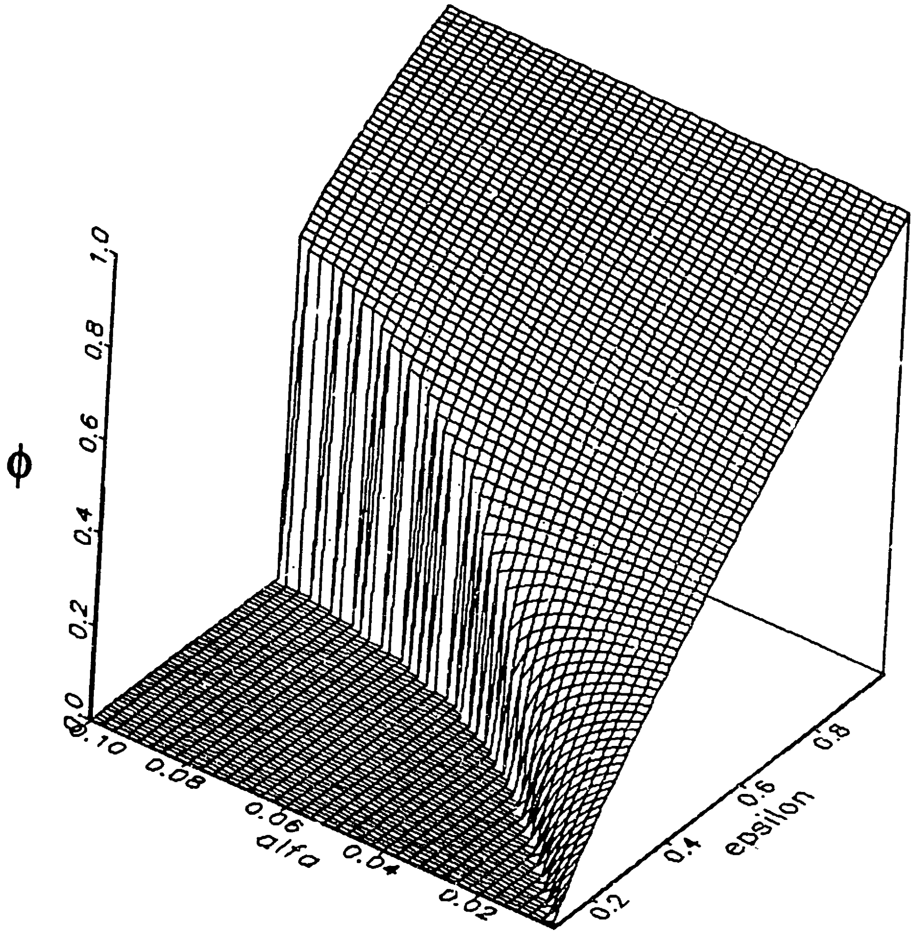


Figure A.III.2

Spillover Contribution $\phi(\alpha,\varepsilon)$

k=.2, Cobb-Douglas Production Function

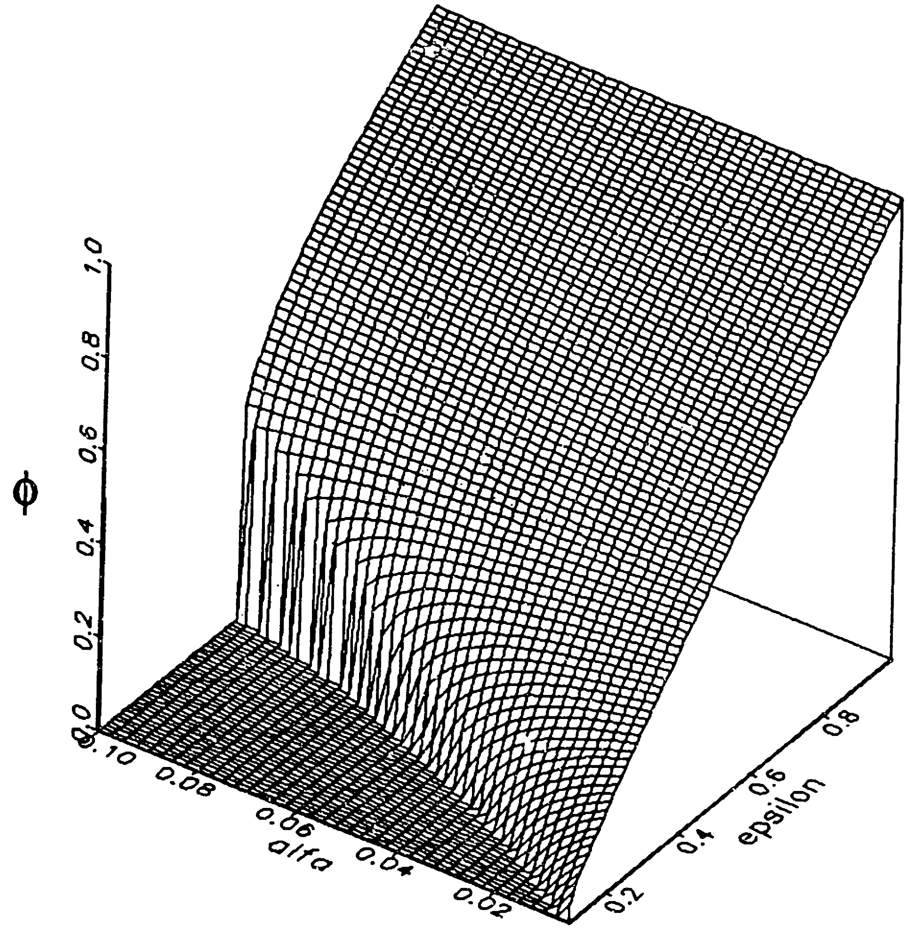


Figure A.III.3

R&D Intensity Z*/(1-Z*)

k=.1, Cobb-Douglas Production Function

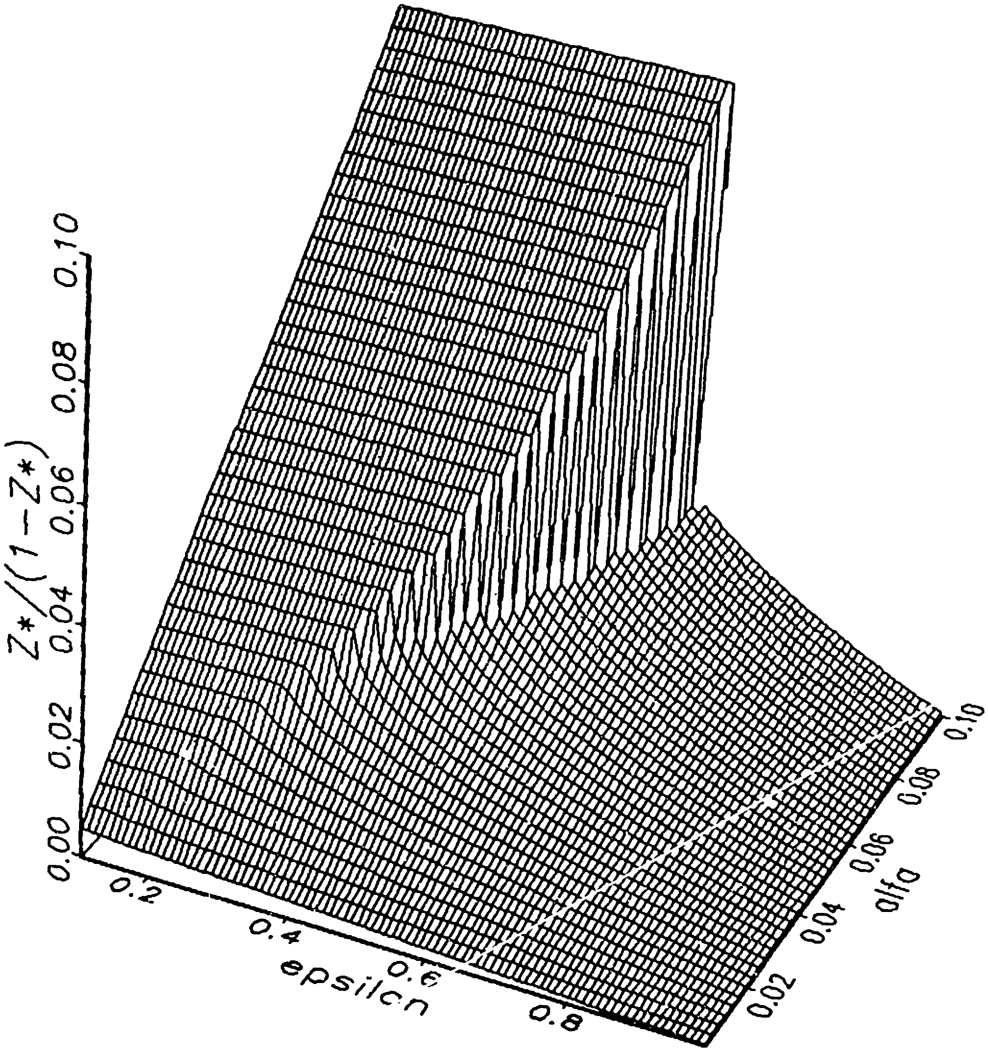
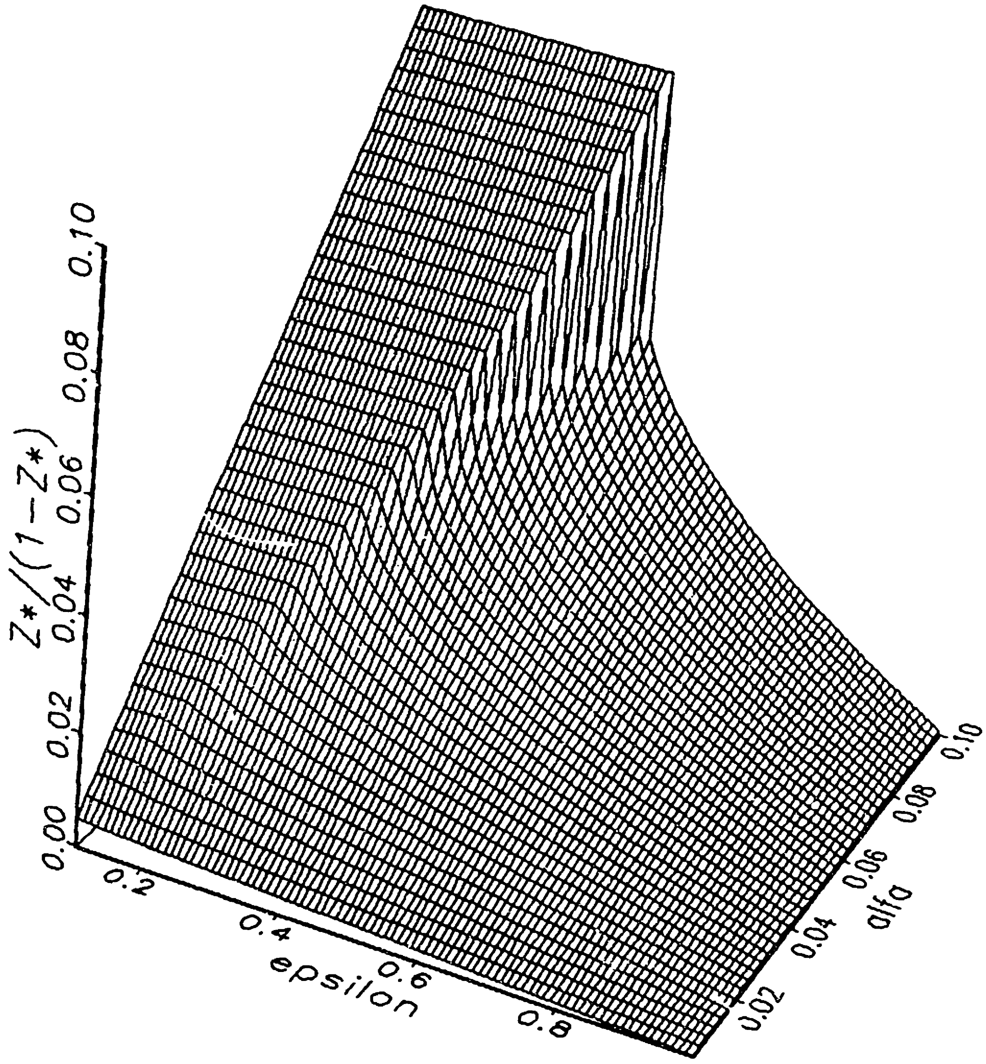


Figure A.III.4

R&D Intensity Z*/(1-Z*)

k=.2, Cobb-Douglas Production Function



Chapter IV

Preemptive and Nonpreemptive R&D Incentives in Vertical Relationships

IV.1 Introduction

The previous chapter analyzed the incentives of a monopolist supplier to generate information spillovers for a downstream sector in order to accommodate entry into the downstream industry. I derived conditions under which accommodating entry was profitable for the supplier, even at the cost of reduced downstream R&D incentives.

In this chapter, I analyze two additional strategic appropriation mechanisms involving intentional spillover production by a monopolist supplier: the promotion of downstream innovation and the preemption of downstream R&D efforts that may lead to the emergence of market power among the supplier's customers. I demonstrate here that the supplier will promote downstream innovation if the introduction of new technologies occurs too slowly, and that it will preempt downstream innovation if a downstream innovator could obtain a patent and restrict the post-innovation output of the downstream industry.

I use a simple timing framework in which firms choose the pace with which they will develop an innovation with given technological characteristics. To simplify the argument I will assume that the R&D technology is deterministic, i.e. the innovation date is a nonstochastic function of the firm's R&D investment.[1] Downstream firms seek to obtain the innovation because the winner of the R&D race is awarded a prize in the form of a temporary patent monopoly. The upstream supplier is interested in downstream innovation, since changes in downstream production costs or product quality will increase the demand for the supplier's intermediate good.

The timing framework depicts R&D in a different way than the previous model did. R&D is organized in separate innovation projects with exogenously given profit implications. Research and development efforts are described as a race in time. In many cases, this appears to be a realistic characterization of R&D - firms in real-world markets often attempt to be the first with a given innovation because the pioneering position is frequently associated with significant advantages.[2] Due to the assumption of a deterministic R&D technology, the firm with the greatest valuation for the innovation will choose the fastest development pace and succeed first.

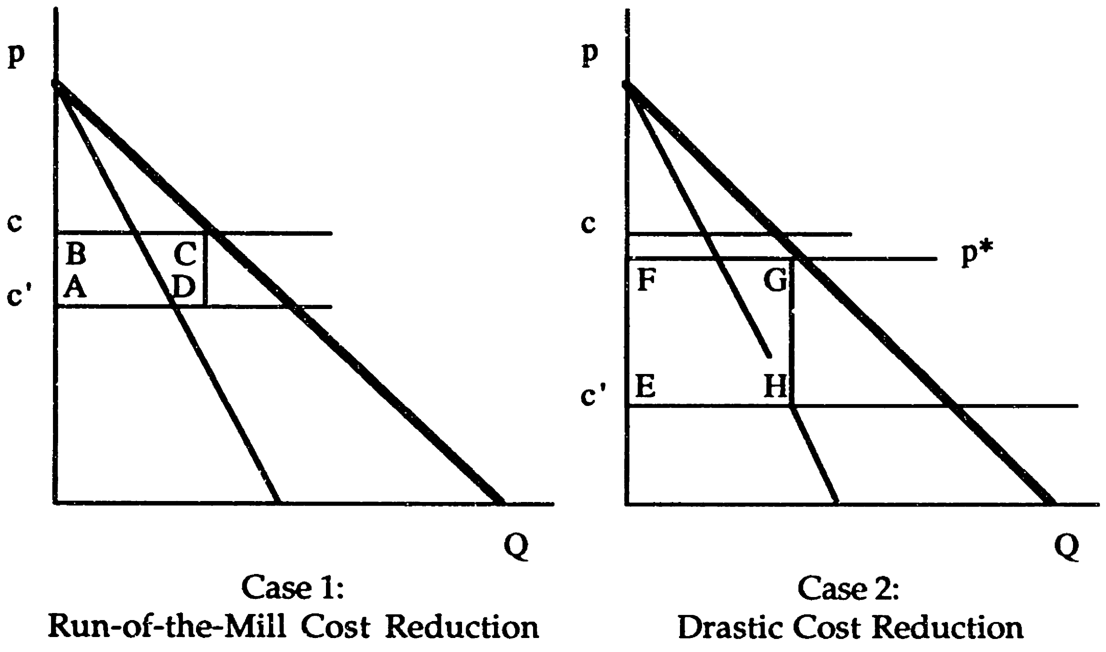
For most of this chapter I will take as given that licensing and vertical integration are not feasible or profitable for the monopolistic supplier.[3] The validity of these assumptions has already been discussed in the previous chapters of this thesis. However, it should be pointed out that in some cases the strategic appropriation mechanism can produce a first-best result for the supplier so that integration and licensing would not offer any improvement even if they were perfect instruments to extract rents. If licensing were an efficient and costless alternative or if firms could costlessly integrate into any production activity, then the identity of an innovator as a supplier or buyer would have little meaning. It would always be possible to sell the ownership title to the agent with the greatest valuation for the technology (von Hippel 1982). But once one assumes that vertical integration and licensing are imperfect or infeasible options for the supplier firm, there is an important asymmetry in the payoffs from downstream innovation. The supplier now appropriates an externality benefit from enhanced factor demand while a downstream innovator receives returns from using a new process or selling a new product. To predict patterns of investment and the likely source of the innovation, the innovation incentives have to be compared given this asymmetry in the benefit distribution.

The payoff structure in this R&D game also has to reflect an important vertical distortion. Ceteris paribus, the monopolistic supplier always prefers a competitive downstream industry to an oligopolistic one in order to avoid a restriction of output in the vertical channel. In particular, a competitive downstream industry in which all firms have access to an innovation is preferred to a setting in which intellectual property rights for the innovation are under the ownership of one or a few downstream firms. Therefore, the supplier's R&D incentives will be partially driven by the motivation to avoid any form of vertical distortion.

Ex ante incentives for innovation can exist only if the post-innovation market structure deviates from the ideal of perfect competition. Otherwise, revenues will just cover post-innovation production costs, while the R&D outlays made by the innovator cannot be recouped (von Weizsäcker 1980).

But rent extraction in the post-innovation market will induce a restriction of output, no matter whether the innovation is of the "run-of-the-mill" or "drastic" type. Figure IV.1 displays the two cases, following the well-known classification by Arrow (1962) and Nordhaus (1969, p. 70). The left half of figure IV.1 depicts the case of a "run-of-the-mill" innovation. The innovator has been able to reduce production costs from the ex ante level c to the post-innovation level c'. However, the cost reduction is not sufficient to monopolize the industry. The innovator has become a dominant firm, but its pricing is constrained by the existence of the old technology. The innovator may be able to license its technology at a rate of c-c' per unit of production, but total industry output will still be limited to the ex ante level, and not expanded to the level that would be possible with perfect competition. The maximum profit rate that the innovator can expect to capture without discrimination is given by the area of the rectangle ABCD.

In the case of a drastic innovation, the monopoly price p* corresponding to a level of production cost c' is sufficiently low to exclude all other firms from production. The innovator will become a monopolist in the ex post market and appropriate the profit rate EFGH. Pre- and post-innovation output of the downstream industry will differ in this case, but the monopoly leads again to restricted output if compared to an industry in which competitive firms would use the low-cost technology.



Case 1:
Run-of-the-Mill Cost Reduction

Case 2:
Drastic Cost Reduction

Figure IV.1
Output Effect of a Cost-Reducing Innovation

In both cases depicted in figure IV.1 the innovator can restrict output to a level above that of a perfectly competitive industry. I will use the term "market power" to refer to this ability of output restriction. The emergence of market power (in the aforementioned sense) deprives the supplier of the possibility to sell more of its commodity to downstream producers. The model developed below suggests that if a vertical distortion of this type exists and if R&D investments generate innovations in a deterministic manner, then a monopolist supplier will always innovate before downstream firms do so. The supplier will be the first to innovate for two distinct reasons. If the benefit stream generated by the innovation accrues largely to the upstream supplier or if appropriability conditions are weak in the downstream industry, then the supplier's preferred innovation time may predate any profitable downstream innovation date. In other words, the supplier promotes downstream innovation by introducing the new technology earlier than any of the downstream firms could do. However, even if the competitive innovation time in the downstream industry predates the supplier's preferred innovation time, the supplier will still want to innovate preemptively. A simple model of preemption reveals that the supplier's preemption incentives are driven by its desire to avoid a vertical distortion arising from a downstream patent monopoly, even if it is only temporary.

The model thus makes the stark prediction that any innovation enhancing the supplier's profits will originate with the supplier. The supplier will innovate, either at its own preferred innovation date or just fast enough to preempt any of the downstream firms. In both of these cases the R&D results will be provided as a public good to the downstream firms. Thereby the monopolist can enjoy the full benefits of innovation in the form of an externality benefit while maintaining the competitive structure of the industry in which the innovation is adopted. Absent further vertical distortions (e.g. from variable proportions problems) this strategy will produce a first-best profit for the supplier.

This result is surprisingly strong, but loses its bite once one considers alternative assumptions. The paper discusses three premises that add more realism to the model. I consider the effect of a stochastic R&D technology, of heterogeneities across downstream firms, and the implications of imperfect information transfer. The latter two problems may cause the supplier's innovation cost to be higher than those of individual downstream firms. Alternatively, the supplier may have to set incentives for downstream firms to engage in private learning and adoption efforts in order to assimilate the technology produced by the supplier. Due to their sunk cost character these investments may require a vertical distortion and diminish the supplier's profit. Finally, I discuss how the results are likely to change if one allows for ex ante industry configurations other than a perfectly competitive downstream industry and an upstream monopoly.

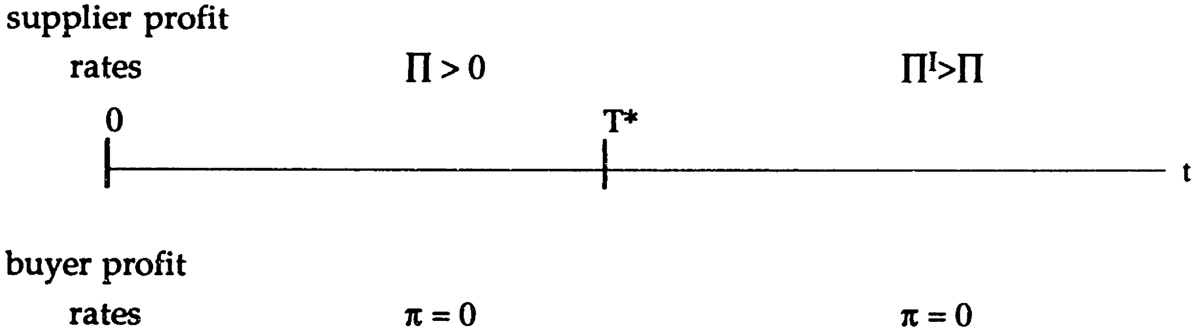
The rest of this chapter proceeds in four main sections. Section IV.2 introduces the model and shows that under very simple assumptions the supplier will always be the source of innovation. Section IV.3 considers three alternative assumptions (stochastic R&D technology, idiosyncratic production technologies, and "sticky data" problems). Section IV.4 extends the model to oligopolistic industry structures. Section IV.5 summarizes and discusses the results.

IV.2 The Model

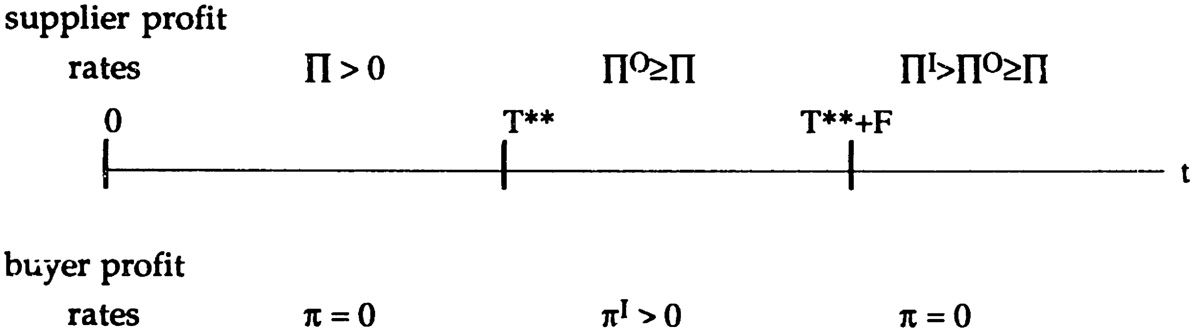
IV.2.1 Assumptions

I adopt the deterministic R&D game developed by Gilbert and Newbery (1982) and apply it to R&D competition between vertically related firms. I assume that a monopolistic supplier faces a buyer industry which is perfectly competitive ex ante. The supplier or any downstream firm can engage in R&D efforts which will produce a new downstream production technology or product with certainty. Vertical integration and licensing are infeasible by assumption.

I first summarize the timing and payoff structure and then describe assumptions regarding the deterministic R&D technology. The payoff structures and timing are displayed in Fig. IV.2.[4]



Case 1: Upstream Innovation and Complete Spillovers



Case 2: Downstream Innovation

Figure IV.2
Timing and Payoff Structure

Consider the timing and the payoffs when the innovation originates with the supplier.[5] This is depicted as Case 1 in Fig. IV.2. Let the innovation date be T^* in this case. The supplier is assumed to have a constant pre-innovation profit rate Π. Once it has concluded the innovation project, it transfers the new technology to all downstream firms and makes it available to them as a public good. Adoption by downstream firms takes place instantaneously and the supplier's ex post profit rate is Π^I. It is assumed that $\Pi^I > \Pi$, i.e. the innovation is strictly profit-enhancing for the supplier. This assumption essentially excludes supplier incentives to preempt and "shelve" innovations that have a negative impact on upstream profits. The downstream industry is assumed to be competitive ex ante, i.e. firms make zero profits prior to the innovation. Since all downstream firms adopt the new technology instantaneously once it becomes available, the downstream profit rates will also be zero after innovation has occurred.

The same innovation can be brought along by any firm in the downstream buyer industry (Case 2). Let the innovation date be T^{**} under this scenario. Pre-innovation profit rates for downstream firms are again equal to zero, but the successful innovator is assumed to win a prize, i.e. it receives the flow profit $\pi^I > 0$ for a given time F where $F \in (0,\infty)$. F can be interpreted as the lead time that the innovator enjoys due to an imperfect patent. Imitators can "design around" the patent after F years, enter the market and transform the industry into a perfectly competitive one with $\pi=0$ for all firms. The case of a perfect patent $(F \rightarrow \infty)$ is nested in this specification of appropriability conditions. If the innovation originates in the downstream industry at time T^{**}, the supplier's profit rate will be $\Pi > 0$ prior to innovation, $\Pi^O \geq \Pi$ while the downstream innovator receives positive flow profits, and $\Pi^I > \Pi^O \geq \Pi$ once imitators have transformed the downstream industry to a perfectly competitive one. This ordering of profit rates reflects the presence of the vertical externality.

Both firms employ the same R&D technology and have complete information. R&D projects can be characterized by the deterministic cost function C(T) measuring the discounted cost of reaching innovation at time T. C(T) is assumed to be strictly decreasing in T, i.e. choosing innovation to occur sooner is costly.[6]

Let r denote the common interest rate. To ensure quasi-concavity of the objective functions derived below and to exclude the trivial case of innovation at T=0, let me make the standard assumptions (Fudenberg and Tirole 1985; Reinganum 1981)

Assumption 1) $(C(T)\exp(rT))' < 0\ \forall T$,

Assumption 2) $(C(T)\exp(rT))'' > 0\ \forall T$,

Assumption 3) $\Pi^I - \Pi \leq -C'(0)$, and

Assumption 4) $\pi^I (1-e^{-rF}) \leq r\, C(0)$.

The first two assumptions assure that the "current R&D costs" are decreasing in the innovation date, but at a decreasing rate. The last two assumptions exclude the possibility of innovation by supplier or downstream firm at time T=0. A particular cost specification[7] to be used later is given by

Assumption 5) $C(T) = \lambda e^{-(r+\omega)T} \quad (\lambda > 0, \omega \geq 0)$.

In this specification, λ is a scaling parameter and ω can be interpreted as a measure of exogenous technical progress: as time goes by, new technologies can be used to make the development process cheaper. Hence, if ω is greater than zero the firm can save resources by slowing the development pace. Conversely, it is costly to accelerate R&D efforts. Another interpretation of the parameter ω can be based on Peck and Scherer (1962) and Brooks (1975) who point out that R&D projects require more communication once team size is increased for the purpose of acceleration. ω will then be an indicator of how costly enhanced coordination is, as the R&D project is accelerated. Dierickx and Cool (1989) refer to these cost relationships as "time compression diseconomies." Note that for given payoffs the parameter λ has to be restricted to some range $\lambda>\lambda_{min}$ to satisfy assumptions 3 and 4. Otherwise the

R&D project would be so inexpensive that firms would try to innovate instantaneously.

A final assumption concerns the vertical externality. I assume that the innovation in the downstream industry introduces a vertical distortion such that

Assumption 6) $\Pi^I > \pi^I + \Pi^O$.

This assumption is critical, but follows directly from the above arguments (Spengler 1950). If the downstream industry structure is competitive ex ante, innovation can lead to the emergence of of a monopoly or a dominant firm. Thus, if a downstream firm innovates, joint profits of the upstream monopolist and the downstream innovator will be lower than the profit of the supplier who innovates preemptively and provides the technological knowledge as a public good. Assumption 6 states this relationship for flow profits.

IV.2.2 Nonpreemptive Supplier Innovation

A monopolistic supplier is said to have nonpreemptive R&D incentives if its preferred innovation date T^* precedes the earliest profitable downstream innovation date T^{**}.

The supplier's preferred innovation date is the solution to the "stand-alone"[8] maximization problem

$$\text{(1)} \qquad \max_{\{T\}} \; V = \int_0^T \Pi \, e^{-rt} \, dt + \int_T^\infty \Pi^I e^{-rt} \, dt - C(T) \quad .$$

The first-order condition for this maximization problem implicitly defines the monopolist's nonpreemptive invention time T*

$$\text{(2)} \qquad (\Pi^I - \Pi) \, e^{-rT^*} + \frac{dC(T)}{dT} \bigg|_{T^*} = 0 \; .$$

Given assumptions 1 and 2, T* is the unique solution to the maximization problem (1). Assumption 3 assures that T* is positive. Equation (2) reflects the well-known result that a single innovator lacking any competition in the R&D race will time its R&D project such that the increase in discounted profit will be equal to the marginal cost of an R&D program with invention time T*.[9] The larger the gain from the new technology the faster will be the pacing of the firm's R&D project. By assumption I have excluded cases in which the difference $\Pi^I - \Pi$ is negative. However, if the profit rate using the new technology is equal to or smaller than the profit rate from using the original technology the monopolist will undertake no R&D project (except for reasons of preemption, of course).

I assume that competitive pressures will force firms to dissipate the expected future profits.[10] Downstream innovation will then take place at the earliest possible time T** where T** is defined implicitly through

$$\text{(3)} \qquad C(T^{**}) = \int_{T^{**}}^{T^{**}+F} \pi^I e^{-rt} \, dt \quad .$$

The solution of this equation is positive by virtue of assumption 4. Note that innovation at T** leaves the innovator with zero profits. Innovation before T** is therefore not profitable for any of the downstream firms. As intuition suggests, the downstream competitive date of innovation T** is strictly decreasing in π^I and in the lead time F. While an explicit comparison of the innovation dates T* and T** requires more detailed knowledge of the cost function, a qualitative statement can be made easily. If the increase in the supplier's profit rate ($\Pi^I - \Pi$) is large in comparison to the gains π^I that a downstream firm can expect or if the lead time F of the downstream innovator is sufficiently short, then the supplier will want to innovate sooner than the downstream firms and produce the technological knowledge as a public good.

Using the cost specification given in assumption 5 one can show that the innovation dates T* and T** are given by

$$T^* = -\frac{1}{\omega} \ln \left(\frac{\Pi^I - \Pi}{\lambda(r+\omega)} \right) \tag{4}$$

and

$$T^{**} = -\frac{1}{\omega} \ln \left(\frac{\pi^I (1-e^{-rF})}{\lambda r} \right) \quad . \tag{5}$$

T* and T** are positive as a consequence of assumptions 3 and 4. One can conclude that the monopolistic supplier will innovate at its preferred innovation date T* if

$$T^* < T^{**} \Rightarrow \frac{\pi^I (1-e^{-rF})}{r} < \frac{\Pi^I - \Pi}{r + \omega} \quad . \tag{6}$$

Equation (6) describes the condition under which the stand-alone incentives of the monopolistic supplier are higher than those of the downstream firms. Assuming symmetric information about profit rates, cost function and appropriability conditions, none of the downstream firms will undertake any R&D in this case, since such an investment would only duplicate at time T^{**} the technological knowledge that is already available as a public good at time T^{*}.

To make this result intuitively clear, consider the following example. Let the monopolist be a supplier of a particular material that prior to innovation is not used in downstream production ($\Pi=0$). The innovation is a downstream production process that would allow the buyer firms to switch from a previously used material to the one offered by the monopolist. It is conceivable that the resulting cost reduction in downstream production is small and that the largest share of producer surplus from adoption of the technology accrues to the supplier. Similarly, if the innovation can only be protected for a short period (i.e. the lead time F is short) then the competitive innovation time T^{**} can easily exceed the monopolist's nonpreemptive innovation date T^{*}. In such cases it seems natural that the upstream party pursues the innovation in a nonpreemptive way, since it expects to receive the lion share of the total producer surplus from technological progress.

Since the competitive character of the downstream industry is maintained there will be no ex post distortion due to downstream market power.[11] Absent other distortions the monopolist achieves its first-best solution by producing the innovative technology and spilling it over to downstream firms as a public good. Neither licensing nor vertical integration

- even if they were feasible here - could improve upon the profit stream that the supplier receives.

The modeling of appropriability conditions in the downstream industry reveals an interesting redundancy property of a market economy with inter-industry externalities. It is often alleged that weak R&D incentives in any given sector of the economy imply that comparatively little innovation will occur. However, the monopolistic supplier does not experience any of the externality effects due to spillovers or weak patent protection and may be sufficiently interested to promote innovation in the buyer sector. This redundancy mechanism would not work if the economy were organized in a perfectly competitive way since there are no externalities across vertically related sectors in this case. Note also that weak downstream appropriability (e.g. due to intra-industry spillovers) *causes* the occurrence of inter-industry spillovers in this model.

Besides weak appropriability conditions, there are other factors that may weaken the downstream R&D incentives, but may not necessarily affect the supplier's R&D incentives. For example, risk aversion on behalf of the downstream firms is likely to reduce downstream incentives. The upstream supplier may be able to spread technological risk more effectively than downstream buyers of the commodity. Upstream innovation may then be an attempt to alleviate the underinvestment problem arising under risk-aversion.

Furthermore, if the upstream monopolist could force a potential downstream innovator to accept a nonlinear pricing scheme then the profit rate π^I could be lower than under linear prices. In the extreme case of perfect vertical control by the supplier the post-innovation profit rate of the downstream innovator could be zero. Even if a downstream firm went ahead and developed an innovation, it would not be able to appropriate any benefits since the supplier can extract the profits by charging a fee equal to the profit rate. Full vertical control thus exercised destroys the incentives for innovation in the downstream sector. But at the same time, the incentives for the upstream supplier to perform innovations and transfer them to downstream firms are enhanced since the supply sector essentially "inherits" downstream incentives.[12] The upstream incentives for innovation are identical to those of a firm owning the downstream industry, i.e. the fully integrated structure.

Some of the issues mentioned here have an obvious similarity to problems discussed in the vertical restraint literature. It is well-known that some vertical control instruments (say franchise fees plus marginal cost pricing) can remedy the basic vertical externality. But perfect vertical control can destroy retailer incentives to provide sales-enhancing services (Tirole 1988, p.178). The problem of R&D appropriability is also reminiscent of advertising spillovers among retailers (Mathewson and Winter 1984). If the benefits from advertising or pre-sale services cannot be appropriated fully by retailers, advertising and service expenditures will be too low from the upstream manufacturer's point of view. The effect of risk aversion among retailers and of informational asymmetries has been discussed by Rey and Tirole (1986). However, the analogy between vertical restraint problems and issues raised in this thesis is limited. The prospect of significant technological change is rather unlikely for a downstream industry of retailers while it can be of great importance when the downstream industry consists of manufacturers.[13]

IV.2.3 Preemptive Supplier Innovation

The previous subsection yielded a sufficient condition for the supplier's provision of technological knowledge as a public good to the buyer industry. The condition is not necessary because even if $T^*>T^{**}$, the supplier may still be better off by preempting downstream innovation slightly prior to T^{**} and spilling the generated knowledge over to downstream firms. These incentives are considered here in a model based on Gilbert and Newbery's (1982) analysis of preemption incentives. In their model a monopolist has incentives to preempt an entrant who is seeking to develop a substitute to the monopolist's good. Gilbert and Newbery are concerned about the detrimental effects caused by the monopolist's incentives to "shelve" patents, i.e. to deny society access to a new and potentially welfare-improving technology. In the model developed in this section, the monopolistic supplier has an incentive to grant society free access to a new technology so that the welfare consequences are definitely positive.[14] The same monopolist who tries to prevent the development of substitutes of its own good may have incentives to provide society with complementary goods technologies[15] or cost-reducing innovations. Monopoly power persists, but the monopolist's opportunity to preempt has the beneficial effect of preventing the emergence of market power in other industries which would lead to additional distortions.

As in the previous subsection, let T^{**} be defined by equation (3) as the earliest possible invention date for downstream firms, i.e.

$$(3) \qquad C(T^{**}) = \int_{T^{**}}^{T^{**}+F} \pi^I e^{-rt}\, dt \ .$$

If a downstream firm innovates at time T**, the profit of the monopolistic supplier will be

$$(7) \qquad V^M = \int_0^{T^{**}} \Pi e^{-rt} dt + \int_{T^{**}}^{T^{**}+F} \Pi^O e^{-rt} dt + \int_{T^{**}+F}^{\infty} \Pi^I e^{-rt} dt .$$

The monopolist can preempt downstream innovation by innovating at date T-ε by spending an amount of C(T)+δ(ε). Consider the monopolist's profit in the limit as ε and δ approach zero. If the monopolist chooses to spill the technology over to all downstream firms its profit is:

$$(8) \qquad V_S^M = \int_0^{T^{**}} \Pi e^{-rt} dt + \int_{T^{**}}^{\infty} \Pi^I e^{-rt} dt - C(T^{**}) .$$

Substituting equation (3) for C(T) and rewriting the integral expressions, the value of the preemptive strategy is given by

$$(9) \qquad V_S^M - V^M = \int_{T^{**}}^{T^{**}+F} \Pi^I e^{-rt} dt - \int_{T^{**}}^{T^{**}+F} \Pi^O e^{-rt} dt - \int_{T^{**}}^{T^{**}+F} \pi^I e^{-rt} dt .$$

Note that the value of preemption is strictly decreasing as the lead time F is reduced, since the period during which the upstream supplier has to tolerate a downstream monopoly gets shorter. Preemptive R&D and making the technology available as a public good is nonetheless strictly profitable for the monopolistic supplier if

(10) $\Pi^I - \Pi^O > \pi^I$ or equivalently $\Pi^I > \Pi^O + \pi^I$.

Equation (10) indicates that the monopolistic supplier will find preemptive patenting and spilling over of the generated knowledge profitable if the supplier's profit rate after providing the technology to all firms exceeds the joint profit rates of the upstream and downstream industry after a single downstream firm has obtained a patent. By assumption 6, this is always the case, hence the supplier will always preempt if $T^{**}<T^{*}$. Equation (10) also has the interesting implication that the monopolist will pick the alternative with the greatest producer surplus.

Equation (10) is completely analogous to the key result in Gilbert and Newbery (1982). Gilbert and Newbery show that a monopolist will have incentives to preempt the invention of a substitute by competitive firms if the ex ante monopoly profit is greater than the sum of the duopoly profits after entry (i.e. invention by the entrant) has occurred. The problems are indeed isomorphic in the sense that firms compete in both models for surplus from the final goods market. In the Gilbert-Newbery model, competition is horizontal between the incumbent monopolist and the entrant. In the above model, the upstream monopolist and downstream firms compete for a beneficial allocation of surplus in the vertical system. Tirole (1988, p. 393) offers an intuitive explanation for the Gilbert-Newbery result: "It is reasonable to assume that in a homogeneous-good industry a monopolist does not make less profit than two non-colluding duopolists. (...) We conclude that *because competition reduces profits, the monopolist's incentive to remain a monopolist is greater than the entrant's incentive to become a duopolist*." This "efficiency effect" drives R&D incentives in the Gilbert-Newbery model.[16]

The monopolist's incentives for preemptive R&D in vertical relationships can also be seen as the consequence of an efficiency effect. If an upstream monopolist faces downstream firms with market power, then the market mechanism will lead to double-marginalization. As a result, joint profits are less than optimal. Preemptive R&D can prevent this development and thereby help to maintain first-best rents.

If preemption is certain no downstream firm will have incentives to invest in R&D.[17] But if no downstream firm conducts R&D the monopolist may have incentives to delay its own schedule slightly. The feasibility of this strategy depends mainly on the observability of R&D efforts. If the monopolist can observe the competitive firms perfectly and if it can accelerate its own R&D schedule costlessly, then preemption will always be feasible. Whenever one of the downstream firms made an attempt to develop the new technology, the monopolist would accelerate its own R&D schedule just enough to preempt. Credibility of the preemption threat assured, downstream incentives have been neutralized and the monopolist can still maximize the discounted value from flow profits. The actual date of invention will then be the nonpreemptive date T^*. Conversely, if the monopolist cannot react instantaneously to a downstream R&D project it may be forced to conduct research at the increased pace dictated by the presence of downstream R&D competitors.[18] The time of invention is then the competitive date T^{**}, but the monopolist will be the inventor of the new technology. In both cases only the monopolist conducts R&D. Therefore, the cost for R&D has to be borne only once in the preemption scenario while in the competitive race duplicative projects may have to be financed.

Note further that preemptive R&D in conjunction with complete spillovers will always lead to lower prices for the final good since the competitive character of the downstream industry is maintained. Consequently, both consumer and producer surplus are greater in the preemption case than in the case of downstream innovation. In this model, preemptive R&D in conjunction with intentional inter-industry spillovers is then unambiguously welfare-enhancing. This result is different from the one described in chapter III, since upstream involvement in downstream innovation does not carry any disincentive effects in this simple model.

IV.3 Three Alternative Assumptions

The prediction that a monopolistic supplier will account for all downstream innovations that enhance upstream profits even in the slightest appears extremely strong.[19] It is therefore important to identify the major assumptions that drive this result. Three modelling assumptions are of particular importance here: the deterministic character of the R&D technology, the assumption that the upstream supplier and downstream firms have access to the same information, and the homogeneity of downstream production technologies. A relaxation of each of these assumptions can weaken the result that the supplier will account for all innovations.

IV.3.1 Stochastic R&D Technology

Some implications of a stochastic R&D technology have been discussed by Reinganum (1983; 1984; 1989) and Gilbert and Newbery (1984). In her 1983 paper, Reinganum demonstrates that an incumbent may invest less in R&D than a challenger if the invention process is stochastic and if the innovation is sufficiently "drastic". The intuition for Reinganum's result is that ex ante profits dull the incumbent's R&D incentives in a stochastic race. If the incumbent delays the expected date of invention just slightly, it may lose the race with a somewhat higher probability, but it also spends slightly less and enjoys the ex ante profits for a longer time. Conversely, the challenger has zero profits ex ante and profits from a delay in its R&D pace only by spending less. In other words, since the incumbent only "replaces itself" its incentives are lower than those of the entrant.[20] As equation (10) shows, under certainty the ex ante profit rate Π does not play any role, only the increase or the deterioration of flow profits measured by $\Pi^I - \Pi^O$ matters.[21]

Reinganum's argument can be applied directly to the case of innovations that reduce upstream profits, for example by substituting some new input for the upstream supplier's factor of production. A "drastic" innovation in Reinganum's sense is then an innovation that substitutes the supplier's input altogether. The sole difference between vertical and horizontal competition is here that the threat of substitution does not emerge in the form of a new entrant, but in the form of a new downstream production process.

However, in the case of an innovation that actually enhances upstream profits, Reinganum's elegant calculus arguments cannot be applied directly. In this case, downstream cost reduction or quality improvement is a strategic complement for the supplier.[22] Upstream profit enhancement $\Pi^I - \Pi^O$ from preemption and the size of the downstream prize π^I are positively correlated, i.e. whenever the downstream firm sees a greater reward to winning the race, so does the upstream supplier. Conversely, in Reinganum's model, the innovation is always a strategic substitute and the incumbent's profit rate is nonincreasing in the extent of innovation, i.e., more "radical" innovations in the hands of the challenger can drive down, and eventually wipe out, the incumbent's post-innovation profit rates. The mathematical analysis in the case of strategic complements is more complex[23], but intuition suggests that large ex ante supplier profit rates are likely to weaken the upstream innovation incentives in the stochastic framework. Assume for example that the supplier's ex ante profit rate Π is large in comparison to the gain from innovation $\Pi^I - \Pi$ and that the vertical distortion is small. The downstream winner's profit rate π^I will then be on the order of $\Pi^I - \Pi$. Reinganum's intuitive argument can be applied directly to this situation, with the conclusion that a sufficiently high ex ante profit Π will weaken the supplier's incentives. Note that a stochastic R&D technology need not necessarily reverse the conclusions arrived at in the deterministic setting. Fudenberg and Tirole (Fudenberg and Tirole 1986, p.33) point out that with "little uncertainty" in the R&D technology the efficiency effect may dominate.

IV.3.2 Asymmetric Information and "Sticky Data" Problems

A realistic assessment of the information structure will often reveal that the downstream production process itself generates information that is essential for achieving further cost-reductions. Similarly, the downstream firms will frequently be "closer" to the consumer of the final good, and thereby be better informed about the profitability of various product improvements. Ownership of information-generating assets (like production or sales operations) is evidently one reason for the emergence of informational asymmetries. One would therefore expect that many technological opportunities for generating innovations go unnoticed by the supplier. Obviously, downstream firms will be hesitant to spoil their own innovation rents by revealing such information to the supplier.

But perfect transferability of information is unlikely even if the participants wish to maximize the efficiency of information transfer. Von Hippel (1990) argues that information and data are frequently "sticky", i.e. that they cannot be encoded and transferred easily. Problem-solving is then undertaken more efficiently where the data are accessible in non-encoded form. Under these circumstances, the supplier may want to acquire some information-generating assets for laboratory purposes. This prediction is actually borne out in many industries[24]. However, emulating downstream production processes may be an expensive proposition, especially if it occurs solely for experimentation and not for production purposes. These costs may be high enough for the supplier to stop its own innovation efforts altogether and let downstream firms proceed with their private efforts.

Stickiness of information may not only make the procurement of input information costly, it may also affect the cost of transferring technical information from the supplier to the downstream firms. Generating a new process technology, for example, will often result in the creation of "tacit knowledge" (Polanyi 1958) that is hard to encode and transmit. Consider then a case in which information transfer is not fully efficient in that the downstream firms do not receive the full set of technological knowledge generated by the supplier. Subsequent use of the information that gets transferred yields a smaller profit gain for the supplier than would accrue with fully efficient information transfer. In other words, the profit gain $\Pi^I - \Pi^O$ is smaller than in the case of efficient information transfer. Depending on the degree of inefficiency, condition (10) may no longer hold in this case. Conversely, if downstream firms replicate the non-transmitted information privately, then the sunk cost character of learning and adoption efforts implies a distortion which again will diminish upstream rents. These additional costs are hard to quantify in a model, but they may weaken upstream innovation incentives sufficiently such that downstream innovation incentives dominate the incentives of upstream firms.

IV.3.3 Idiosyncratic Downstream Production Technologies

Even with negligible transfer costs the supplier may have to incur additional expenses in order to produce a ready-to-use technology for downstream use by a large number of firms. Such costs are likely to arise if downstream firms have idiosyncratic production technologies. This assumption implies that the monopolistic supplier needs to transfer not only one technology that is unspecific with respect to the identity of the downstream firm, but several technologies that are to some degree tailored to specific needs. Alternatively, the upstream producer would be forced to offer a general-purpose technology that can be used by all downstream firms. The cost of producing such a technology are probably greater than those of generating a firm-specific innovation with identical cost-reduction or quality-improving effect. This argument is similar to one employed by Riordan and Williamson (1985), who argue that a general-purpose technology is either more costly or (at identical cost) less efficient than a specific technology.

This argument can be formalized by assuming that the upstream supplier faces a cost relationship $\underline{C}(T) = \alpha C(T)$ where $\alpha \geq 1$. $C(T)$ is the cost function for producing a firm-specific version of the technology at time T and $\underline{C}(T)$ is the cost of generating the general-purpose version that can be readily employed by heterogeneous downstream firms. The parameter α can be interpreted as a measure of the cost disadvantage that the supplier incurs due to downstream idiosyncrasies. Both the nonpreemptive and the preemptive incentives of the supplier will be weakened by the requirement to facilitate downstream adoption by all or a large number of firms. For example, preemption is now profitable for the supplier if

$$(11) \qquad \Pi^I - \Pi^O > \alpha\pi^I \text{ or equivalently } \Pi^I > \Pi^O + \alpha\pi^I.$$

Depending on the value of the parameter α and the payoffs, this equation may or may not hold. The degree of the cost disadvantage and the payoff structure will now determine whether the supplier preempts or not. The nonpreemptive incentives are weakened accordingly.

IV.4 R&D Incentives in Oligopolistic Buyer and Supplier Industries

So far I have only discussed a very stylized vertical organization of production activities. Both monopolies and perfectly competitive industries are rare phenomena in the real world, and vertical combinations of the former with the latter are even more of an abstraction. The purpose of this section is to explore how changes in industry structure will affect the results of the model.

IV.4.1 Downstream Oligopoly

The supplier's control over an innovation may have two distinct effects: it may enable the supplier to facilitate entry beyond the ex ante number of downstream firms, or it may just enable the supplier to prevent the emergence of an industry that is even more concentrated than it was in the ex ante state. This distinction does not matter if the downstream industry is organized in a perfectly competitive way to start with. Prevention of further concentration is in this case identical to creating a perfectly competitive industry.

If ownership of the technology allows the supplier to invite any firm into the downstream industry, then the analysis of preemption incentives from section IV.2 still holds, since the reward structure has not changed. The upstream supplier is again motivated by its profit gain Π^I - Π^O, while downstream firms see the profit rate π^I as their reward. The non-preemptive incentives are even stronger in this case, since the supplier can do away with an ex ante vertical distortion. However, the assumption that entry conditions depend solely on access to one technology is a rather strong one. The ex ante industry structure will in many cases be a reflection of scale economies, sunk cost expenditures, and other factors that are unrelated to the innovation. In other words, the innovation will rarely be so "revolutionary" that it changes production relationships altogether.

A more realistic view is that the supplier may be able to prevent *further* concentration in the downstream sector, including the emergence of a dominant firm (i.e. a constrained monopoly). This would be the case, for example, if the maximum number of firms in the industry were limited by economies of scale, but R&D competition for a patent could reduce this number further. In the following I will focus on this case.

The analysis of the downstream oligopoly case has to take into account then that downstream industry structure determines to what degree an innovation of given "size" improves upstream profit rates. The following stylized model demonstrates the interaction between upstream R&D incentives and downstream structure. I will assume here that the ex ante upstream and downstream industry structures are given exogenously.

There are *n* firms in the downstream industry while the supply sector is owned by a monopolist. The innovation in question is an improvement of downstream product quality. If one of the downstream firms innovates first, then it is awarded a temporary patent monopoly as specified in section IV.2. The downstream oligopolists compete in a race and dissipate all of the rents from being a temporary monopolist. If the supplier innovates, it can again transfer the innovation costlessly, but only to *n* downstream firms since additional firms cannot enter the industry. Ex ante demand conditions are given by

$$(12) \qquad p_0(Q_0) = Q_0^{-\varepsilon} \quad (0<\varepsilon<1) \quad .$$

Customers' valuation of the improved final good is higher than in the ex ante case and only the new product is bought by customers. Ex post demand conditions are described by

$$(13) \qquad p_1(Q_1) = \sigma Q_1^{-\varepsilon} \quad (\sigma>1,\ 0<\varepsilon<1) \quad .$$

To keep the model simple, assume further that the upstream monopolist has unit production costs equal to zero and that downstream firms use a production technology with fixed proportions. Ex ante upstream profits are then given by

$$(14) \qquad \Pi = \beta Q_0{}^{*} w \quad .$$

where w is the per unit price that the monopolist charges for its commodity and β is the proportion of the supplier's commodity per unit of final output. All other factors of production are procured in competitive markets at zero price so that downstream marginal cost are equal to the factor price w. Q_0^* denotes the downstream industry's equilibrium output prior to innovation. Due to the assumption of isoelastic demand for the final good, the factor demand function is also isoelastic, and the supplier's factor price w will be the same prior to and after downstream adoption of the innovation. The improvement of the supplier's profit rate stems only from increased downstream production then, since the upstream price-cost margin is not affected by the innovation.

If the downstream firms maximize their profits by choosing their output, then the Nash equilibrium industry outputs Q_0^* and Q_1^* will be given by

$$(15) \qquad Q_0^* = \left(\frac{w}{1-\varepsilon/n}\right)^{-1/\varepsilon} \qquad \text{and}$$

$$(16) \qquad Q_1^* = \sigma^{1/\varepsilon}\left(\frac{w}{1-\varepsilon/n}\right)^{-1/\varepsilon} \quad .$$

Consider now the monopolist's gain from innovation in the nonpreemptive case. The difference between ex ante and ex post profit rates is given by

$$(17) \qquad \Pi^I - \Pi = \beta w\,(\sigma^{1/\varepsilon} - 1)\left(\frac{w}{1-\varepsilon/n}\right)^{-1/\varepsilon}$$

which can be shown to be strictly increasing in the number of downstream firms n. Similarly, the supplier's preemptive incentives are determined by the difference between Π^I and Π^O which is also increasing in n:

$$(18) \qquad \Pi^I - \Pi^O = \beta w \sigma^{1/\varepsilon}\left(\frac{w}{1-\varepsilon/n}\right)^{-1/\varepsilon} - \beta w \sigma^{1/\varepsilon}\left(\frac{w}{1-\varepsilon}\right)^{-1/\varepsilon} \quad .$$

These results are a direct consequence of oligopolistic behavior. In order to make a profit, oligopolists restrict their output in some way. Hence, the supplier's incentives are affected by the restriction that the ex post number of firms in the downstream industry cannot exceed *n*. Note that the special assumptions regarding demand and nature of competition were made for expositional reasons only. All that is needed to derive this conclusion is a downward-sloping demand schedule and the assumption that output is likely to be the more restricted, the fewer firms operate in an industry.

Conversely, the size of the downstream reward is not affected, since downstream firms are motivated to become ex post monopolists in the downstream industry. In other words, since a downstream oligopoly restricts the supplier's return to innovation, but since it does not necessarily restrict the rents of a future downstream monopolist, the supplier's incentives are weakened.

This argument becomes particularly clear in the case of a bilateral monopoly. Clearly, it would never pay the upstream firm to preempt. Preemption has zero value to the supplier since the ex post structure will be a monopoly in any case. Whether it is still profitable to preempt innovation by one of *n* oligopolists depends on demand conditions and production technology.

The crucial assumption here is that supplier innovation cannot transform the downstream industry back to a perfectly competitive one, while downstream innovation can still yield a monopoly. This asymmetry ties the supplier's hands, while it does not weaken downstream incentives. If the innovation is such that its ownership conveys perfect control over entry conditions to the upstream supplier, then the ex ante oligopoly is merely a temporary phenomenon and does not affect the supplier's incentives. Conversely, if a downstream innovator can only improve its oligopoly rents (rather than get a monopoly), then downstream incentives are weakened, too, and the outcome of the game depends on the exact specification of the innovation payoffs. Obviously, this preemption model cannot produce simple results once one drops the stark assumption that successful innovation yields at least a temporary monopoly.

In conclusion, this section suggests that the monopolistic supplier's preemptive incentives are increasing with the ex ante number of downstream firms if the supplier's control over the innovation can only prevent further concentration in the downstream industry, but not facilitate new entry. It should also be noted that a downstream oligopoly with linear pricing by the monopolistic supplier results in a vertical distortion so that integration or nonlinear pricing may become superior options for the supplier.

IV.4.2 Upstream Oligopoly

Let me assume here that the downstream industry is again organized in a competitive way, but that the supply industry consists of *m* oligopolists. These oligopolists produce an undifferentiated commodity. What is then the payoff structure that motivates upstream oligopolists to innovate?

The answer to this question is ultimately determined by assumptions regarding appropriability. Assume for example that upstream innovators can tie their innovation to their own commodity output, i.e. downstream firms can be restricted to use the innovation only in combination with the upstream innovator's factor of production. The tying restriction is in all likelihood illegal (Posner and Easterbrook 1981, pp. 777-857), but not unheard of in practice (VanderWerf 1990b). If the innovation is drastic in the Arrow-Nordhaus sense (i.e. sufficient to exclude downstream firms who do not adopt it from further production), then ownership of the patent will also produce an upstream monopoly (which may be only temporary). Consequently, upstream oligopolists would seek to be to the first to patent and - according to the assumptions in this simple model - dissipate the expected monopoly rents.

If the tying cannot be enforced (which in all likelihood is the more realistic assumption), then downstream firms who have adopted the innovation can still purchase their commodity input from any upstream firm. Clearly, they have an incentive to do so in order to maintain the limited price competition between upstream oligopolists. Hence, there is a free-rider effect despite the assumption that a patent is awarded to the innovator. Even during the duration of patent protection, an upstream innovator will not be able to appropriate monopoly rents, since the innovation is still a public good to all suppliers. We should expect then that the incentives for supplier innovation are much stronger in tight upstream oligopolies than they are in more competitive supply structures.[25] This is of course a direct implication of the assumption that the supplier firms' output is an undifferentiated commodity. Differentiation leads (at least in tendency) back to a monopolistically organized supply sector.

IV.5 Discussion

A firm's research and development efforts are driven by the incentive to maintain existing rents and to create new ones. In many models (e.g.

Gilbert and Newbery 1982, Reinganum 1983) preemption in R&D has been identified as a tool to prevent a deterioration of profits. This view is based on the implicit assumption that a preemptive strategy can only be applied to strategic substitutes.

The model developed here has presented little in terms of a new model structure. All the tools used here are very familiar to economists. However, by applying the well-known Gilbert and Newbery (1982) model to vertical relationships, a different set of preemption results can be derived. The model now demonstrates that preemptive strategies may also play an important role in improving a monopolist's capability to capture rents by preventing the emergence of market power in vertically related industries. Besides having obvious benefits for the preempting firm, the strategy is also welfare-enhancing, since it avoids welfare losses from double-marginalization.

Preemption of a complementary innovation appears odd at first, since the monopolist is likely to gain anyway from an innovation in a downstream or complementary goods industry.[26] It is the fact that this gain is only suboptimal that drives the results presented here. A monopolistic supplier is therefore willing to preempt downstream competitive firms if it can thus prevent the emergence of a patent monopoly in the downstream industry. If an initial distortion in the form of a downstream oligopoly already exists and if the supplier can only prevent further concentration of the downstream industry by preempting innovation, then the supplier's incentives are dampened, while downstream oligopolists still see a monopoly as their prize. Due to a free-rider effect, the incentives for supplier innovation are also dampened if the supply industry is in the hand of more than one firm. The supplier's inclination to generate a technology for downstream use and spill it over is therefore the stronger (i) the fewer firms operate in the supply sector, and (ii) the more firms operate in the downstream industry.

If patent protection is weak, then the nonpreemptive incentives of the supplier may prove to be more important.[27] The crucial point here is that a monopolistic supplier is not subject to appropriability failures (e.g. spillovers) at the downstream level, and may therefore seek to develop new technologies before any of the downstream firms can afford to. Due to a free-rider effect these incentives are likely to be reduced if the upstream industry is shared by more than one firm, and if the downstream industry is organized oligopolistically. But an upstream oligopoly does not render the argument completely invalid. The two sectors may still experience different disincentive effects, and a shift of R&D incentives to the more concentrated sector may prevail.

In practice, the incentives discussed here appear to have some relevance. In the language of R&D managers, patents covering downstream products or processes are called "usage patents" and are of great importance in many materials-producing industries. Assume for example that a chemicals producer has invented a new man-made fiber. If a usage patent is in the hands of one or few downstream firms, then both firms are in a position to block each other's business in the market or application covered by the "usage" patent. Cross-licensing may be profitable in this situation, but the inventor of the fiber would prefer to have control over both technologies in order to avoid rent-sharing. It is therefore not surprising that materials producers often try to assemble a set of strong patents in various application areas without ever integrating into the production of the final goods. For example, Du Pont frequently designates some of its patents for "customer-use".[28] Customers of Du Pont are given free access to the patented technology.

I have shown in this chapter that R&D incentives can be very sensitive to structural aspects of vertical relationships. Producers in tightly oligopolistic industries have an incentive to see their downstream markets grow. The intuition for this result is simple. The closer industry structure is to a monopoly, the more firms will care about the overall market size rather than their own market share. Even a free-rider effect may then not deter investment in intentional spillover production. Ceteris paribus, more concentrated supply sectors should have greater incentives to either promote downstream innovation or to prevent the emergence of market power. In addition, I have shown that upstream involvement in downstream innovation translates into relatively small market growth if downstream firms restrict output in order to generate rents. The conclusion is that suppliers facing largely competitive industries will have greater incentives to engage in R&D activities that are usually performed by their downstream customers.

The next chapter develops hypotheses based on these conclusions and presents an empirical test using cross-sectional industry data.

FOOTNOTES FOR CHAPTER IV

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[1] The implications of a deterministic R&D technology are discussed in the body of this chapter.

[2] The advantages of being first are discussed in a paper by Glazer (1985). See also Lieberman and Montgomery (1988).

[3] Note that the assumed inefficiency or infeasibility of licensing does not necessarily contradict the assumption of patent protection. A patent excludes others from using a certain invention, but it does not necessarily assure that the ownership title to a technology can be transferred efficiently.

[4] The assumption regarding payoff structure and timing are similar to those made by Katz and Shapiro (1984). The specification used here is less general for expositional reasons. For example, I simply exclude the case in which development costs are too high for one of the parties. I also neglect mathematical intricacies of the Δ-game formulation used by Katz and Shapiro.

[5] In this simple model, the date of invention is also the date of innovation. An innovation is put to use in the very moment that the new technology is invented. While this is a naive description of the R&D and innovation process, it is not restrictive. The model can easily be modified as a characterization of an innovation race in which firms have to go through several R&D stages.

[6] The concept of a time-cost tradeoff in R&D is discussed in detail in Scherer (1984a, pp. 59-64). For a detailed discussion of timing and development expenditures in the area of software development, see Brooks (1975). See also footnote 3 in Gilbert and Newbery (1982).

[7] This specification has been used by Barzel (1968) and Scherer (1967), though with different conceptualizations motivating it.

[8] The term "stand-alone" incentive has been introduced by Katz and Shapiro (1984).

[9] See for example Scherer (1967) or Fudenberg and Tirole (1985).

[10] I use an extreme assumption here by suggesting that competitive firms engaged in a race will dissipate the future rents from innovation completely. This constitutes a bias <u>against</u> the monopolist who "competes" against downstream firms in order to be the first.

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[11] There may be other vertical distortions, for example if the downstream firms produce according to a production function with substitution possibilities, i.e. the factor proportions depend on factor prices. See Tirole (1988, pp. 179-181) for a survey of these issues. Blair and Kaserman (1983) also discuss solutions to the variable proportions distortion.

[12] The price discrimination literature has emphasized the positive effect of third-degree price discrimination on the upstream firm's incentives for innovation. Since this form of discrimination will lead to higher prices in some markets than under a uniform pricing rule, incentives in some downstream sectors may be hurt. The effect on downstream innovation incentives and overall welfare will then be ambiguous.

[13] However, innovations lowering the cost of retailing are not unheard of. The model developed here would suggest that major innovations in retailing should originate with the wholesaler or manufacturer. This hypothesis is testable, but I will not pursue this issue here.

[14] This welfare result is obviously different from the one in chapter III. But in the model developed in this chapter, upstream involvement in downstream innovation causes no disincentive effect as it did in chapter III.

[15] The topic of complementary goods and monopoly has been explored in detail by Telser (1979) who comments on the provision of complementary goods by retailers. Ben-Zion and Fixler (1981) analyze the incentives of a monopolist (the "insider") and a firm in another industry (the "outsider") to provide products that are either substitutes of or complements to the monopolist's commodity. However, they do not consider the preemption incentives arising in this context or the effect of different appropriability regimes.

[16] Preemption and shelving of an innovation may have negative welfare consequences - the term "efficiency effect" refers to the private incentives for R&D.

[17] The following argument regarding the timing of moves in the preemption game is not necessary if one simply adopts the Δ-game specification of Katz and Shapiro. Since the Gilbert-Newbery discussion is intuitively more appealing, I follow their argument.

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[18] As Gilbert and Newbery point out, if one is willing to accept the premise that the monopolist has to preempt and invent the new technology at time T**, an auction market becomes a suitable model of patent competition. Preemption is the Nash equilibrium of the bidding game between the monopolist and downstream firms.

[19] Structural (timeless) models analyzing the extent of innovation can yield a similar result (see Chapter III). Assume for example that entry into the downstream industry is only limited by sunk-cost R&D expenditures. Then the supplier may have an incentive to reduce downstream R&D to zero (accomodating an infinite number of firms) and provide the entering downstream firms with the results of its own R&D efforts.

[20] This "replacement effect" can be interpreted as a conceptual counterpiece to the aforementioned "efficiency effect" (Tirole 1988, p. 395).

[21] Reinganum argues that the stochastic nature of the invention process explains Scherer's (1980, pp. 437-438) observation that "(...) new entrants contribute a disproportionately high share of all really revolutionary new industrial products and processes." The stochastic model developed by Reinganum is not the only scenario in which the entrant may have the upper hand in introducing a new technology. See Scherer (1967) for such a result if the "winner-takes-all" assumption does not hold. A detailed discussion of behavioral aspects of the incumbency problem is presented in Henderson and Clark (1990). Henderson (1990) also provides a detailed econometric study of the investment behavior of incumbents and entrants in the face of generational technical change.

[22] The model applies fully to the case of a monopolistic industry with a competitively organized complementary goods sector.

[23] A general treatment is more complex than Reinganum's (1983) proof, since one cannot exploit the symmetry of payoffs as she does in her model.

[24] Graham and Pruitt (1990, p. 367) describe Alcoa's investment in can-making equipment for its R&D laboratories. Hounshell and Smith (1988) describe similar capital goods investments by DuPont in a number of application areas. See also McKie (1957) for evidence from the tin can industry.

[25] A new aspect of this situation is the possibility of a waiting game which is characteristic of public goods problems. All suppliers prefer the

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innovation to originate in the supply sector, but all of them also prefer some other supplier to go first and develop it. I neglect this issue here.

[26] Strictly speaking this statement only holds for drastic innovations. But by assumption the innovation will not reduce the supplier's profit rate.

[27] Note from equation (9) that the absolute value of the preemption strategy is increasing with the lead time F, while the likelihood of nonpreemptive innovation by the supplier grows as equation (6) shows.

[28] See Gibson (1990, p. 78). Du Pont classifies patents into three categories: for in-house use, for "customer-use", and for licensing purposes. Based on a discussion with patent attorneys in the chemical industry, customer-use patents account for 15 to 25 per cent of all patents in this sector. Note that these arguments suggest that vertical organization should also have some impact on patenting behavior. I pursue this issue in chapter V of the thesis.

Chapter V
Vertical Organization and R&D Incentives - Empirical Evidence

V.1 Introduction

The case studies reviewed in chapter II (section 4) suggest that strategic appropriation can occur in various industries. However, only a very extensive collection of case studies could demonstrate that strategic appropriation incentives have a notable economic effect. The objective of this chapter is to analyze whether such an effect can be detected in a cross-section of industries. The models developed in the two preceding chapters predict that particular forms of vertical organization may support strategic appropriation by providing the necessary interindustry externalities. Based on these models, I develop in this chapter hypotheses relating supply sector organization to the R&D intensity of an industry and test them with cross-sectional data.

The theoretical models in chapters III and IV imply that strategic appropriation has at least two important and empirically observable effects. First, the opportunity to appropriate returns to R&D via a strategic appropriation mechanism is likely to enhance the R&D incentives of the producers of spillover knowledge. Second, since upstream spillover production should lead to greater downstream output or reduced downstream R&D expenditures, downstream R&D intensity should be reduced.[1]

Theoretical arguments suggest that testing for the presence of the second effect appears more promising than trying to identify enhanced supplier R&D incentives. All three mechanisms of strategic appropriation analyzed in the preceding chapters (promoting downstream innovation, accommodating entry, and preventing the emergence of downstream market power) imply that the incentives of supplier firms to provide technological information to downstream firms are strengthened under certain conditions. But it is not necessarily the case that these activities will be accounted for in the supplier firm's R&D budget. Corey (1956) and Mansfield (Mansfield, Rapoport et al. 1971, ch. 5) have pointed out that these expenditures are often borne by the technical marketing and customer service departments of the supplier firm.[2] According to prevailing allocation guidelines (Freeman 1982; OECD 1981) these costs will often not be counted as R&D expenditures. But even if they are, it is not certain that the effect is easily identified, if the dependent variable of the statistical analysis is the upstream industry's R&D intensity. Using R&D intensity data as the dependent variable is often advisable, since the normalization over sales is likely to reduce the effect of other variables like input costs which are usually very difficult to take into account. Since the suppliers' strategic investments should be correlated with enhanced upstream sales, both R&D expenditures and sales will move in the same direction. It may be difficult then to identify any variations in an industry's R&D intensity.

Testing for a reduced downstream R&D intensity does not have these disadvantages. Following the models in chapter III and IV, the suppliers' strategic investments should lead to a reduction of downstream R&D intensity. The sales volume of the downstream industry is supported in part by upstream investments so that the ratio of downstream R&D expenditures over downstream sales should be reduced. This expectation is also consistent with arguments made by Bernstein (1988, p.325) and Cohen and Levinthal (1990a; 1990b). Following these arguments, the empirical analysis described in this chapter explores the effect of supply sector organization on downstream R&D intensity. Since disembodied information flows themselves are difficult to measure, I test for a correlation between supply sector organization and downstream R&D intensity. Obviously, such a test can only produce circumstantial evidence and requires a careful discussion of alternative hypotheses.

The theoretical models in chapters III and IV have focused solely on information spillovers (i.e. disembodied technological knowledge), but in order to enhance the validity of the empirical work, I will also control for inflows of embodied R&D by using Scherer's (1984b) data on interindustry technology flows. The use of these variables is motivated by three concerns. First, it is conceivable that flows of embodied technology may have significant spillover contents with effects on downstream R&D incentives that are very similar to those of disembodied R&D. Consider for example the introduction of a new steel alloy. If such an alloy can be imitated easily by other suppliers, then its introduction has public goods properties for upstream producers. A direct appropriation mechanism will be very inefficient in this case. But such a new alloy may render obsolete some forms of downstream process capabilities, such as knowledge regarding heat treatment or surface hardening of conventional alloys. If such capabilities are in the hands of a few downstream firms, then the introduction of the new alloy would reduce entry barriers for firms seeking to enter the downstream industry. Strategic appropriation is then possible even if the market for the embodied technological knowledge does not work perfectly. For the purpose of my analysis, embodied technology flows may therefore be substitutes for disembodied knowhow developed by downstream firms. The production of such technology flows would then be guided (at least partially) by incentives similar to those explored in the preceding chapters.

A second reason for taking interindustry technology flows into account in the empirical analysis is that the empirical measures of these flows may actually reflect some flows of disembodied R&D as well. In chapter IV, I mentioned that some firms in the chemical industry designate some of their patented technologies for "customer use." Such technological knowledge usually describes process knowledge for use with inputs supplied by the chemical firm. If this behavior is widely practiced, then the measures of technology flows that are based on patent data will be composed of embodied and disembodied R&D.

The third reason for including interindustry technology flow measures in the statistical analysis is to avoid biases due to omitted variables. If flows of embodied and disembodied R&D are correlated, then the omission of either variable will affect the coefficient estimate of the other.

To complement the analysis further, I also use patent data to test a tentative hypothesis regarding the effect of vertical competition between suppliers and buyers on their patenting propensity. I suggest that downstream firms should seek to patent their technology more vigorously if they face "strong" suppliers, since upstream firms often have detailed knowledge about downstream innovation efforts and may disseminate this information among their customers.[3]

The regression results described here strongly support the view that supply sector organization has a significant role in shaping downstream R&D incentives. I find that fragmented buyer industries which receive relatively large cost shares of their inputs from concentrated supply sectors have a significantly lower R&D intensity than sectors relying on more competitive supply structures. Furthermore, relatively concentrated downstream sectors are not subject to this effect. The regression results are also consistent with the hypothesis that firms in fragmented industries use the inflow of technology from external sources as a substitute for their own R&D, but this effect is weakened and eventually reversed as the concentration of the downstream industry increases. These results are consistent with the central predictions from the models developed in chapters III and IV.

I also find that the patenting behavior of sectors strongly dependent on concentrated suppliers differs significantly from patenting propensities in industries with a more competitive supply organization. The data suggest that firms in fragmented buyer industries are more likely to patent when they face "strong" suppliers. I interpret this finding as support for the existence of supplier-promoted spillovers. Facing suppliers who can gather privileged information about downstream technological developments, firms appear to increase their patenting efforts. This behavior presumably strengthens downstream bargaining power in an environment where protection mechanisms like secrecy and lead time have lost many of their advantages.

The remainder of this chapter is structured into four sections. In section 2, I briefly summarize the empirical literature on interindustry technology flows, in particular the contributions by Scherer (1982a), Pavitt

(1984) and Farber (1981). Testable hypotheses based on the literature and on my own theoretical work in chapter III and IV of this thesis are developed in section 3. Section 4 employs a simple linear specification for a regression analysis of two separate equations, the first modelling R&D intensity and the second describing the patenting propensity of an industry. Implications and limitations of this research are discussed in section 5, where I also outline the need for new data sources that permit a more detailed measurement of vertical organization and its effect on R&D incentives.

V.2 Interindustry Technology Flows and R&D Incentives

The theoretical models developed in chapters III and IV dealt only with the intentional production of spillover information, i.e. the supplier's R&D results were disembodied. In this section I briefly summarize some statistical evidence regarding interindustry flows of embodied R&D. Measures of these flows will be used in the statistical analysis to strengthen the validity of the test.

Interindustry technology flows and the vertical organization of production activities have not played a major role in recent theoretical and empirical work on innovation and technological change. This fact is quite surprising, given that institutionally oriented researchers (Pavitt 1984; von Hippel 1988a) have produced persuasive evidence that the composition of supply sectors is often correlated with distinct innovation patterns within a given industry. Structural changes in the American economy have also been linked to changes in input and output flows in Carter's (1970) extensive analysis. In recent econometric studies, Levin and Reiss (1988), and Cohen and Levinthal (1989) have included in their models variables that account for the contributions to innovation made by external sources of technology, e.g. equipment and materials suppliers. But all of these studies have treated the contributions originating in other sectors as exogenously given. The interdependence between R&D incentives of firms in different industries is not yet fully understood.

The importance of R&D performed by other sectors was demonstrated as early as 1967 in research by Brown and Conrad (1967). Regression studies by Raines (1971) and Terleckyj (1974) confirmed the Brown-Conrad result, but they also produced some unexpected estimates.[4] Raines and Terleckyj found that R&D embodied in intermediate and capital goods was a statistically significant determinant of an industry's productivity, but that the industry's own R&D was no longer significant once the measure of embodied R&D was included.[5] However, the measures for embodied R&D used in these early studies do not inspire great confidence. R&D expenditures of a supplier industry are simply distributed according to the distribution of purchases by downstream industries. The true allocation of upstream R&D resources probably differs from the one implicitly assumed in these studies. However, two extensive empirical studies (Pavitt 1984; Scherer 1982a) have provided us with a more precise and detailed description of interindustry technology flows. I summarize the contributions here briefly, since some of these data will be used as independent variables in my empirical analysis.

Scherer (1982a) conducted a major effort to map the technology flows between industries in the United States economy and produced a detailed technology flow matrix. The idea of such a matrix dates back to Schmookler (1966), who used patent data to calculate measures for the rate of production and consumption of novel technologies in several industries. Scherer's efforts were similar, but produced data at a far greater level of detail. Using

443 large US corporations reporting under the FTC line of business survey as his sample, Scherer and associates analyzed the specifications of all 15,112 patents that were obtained by these firms in the period between June 1976 and March 1977. Among other information, patent specifications include data regarding the prospective use of the patented technology. The value of the patent was approximated as the average (per patent) R&D expense incurred by the inventor. The flow measure constructed by Scherer measures then the innovator's R&D expenditures flowing to the sector using the new technology.

	↓ ORIGIN R&D	USING INDUSTRY 1	USING INDUSTRY 2	USING INDUSTRY 3
INDUSTRY 1	20	10	5	5
INDUSTRY 2	34	29	3	2
INDUSTRY 3	19	0	7	12
USE R&D →		39	15	19

Figure V.1
A Technology Flow Matrix

Each industry is conceivably a user of technology produced by other industries and conversely produces technology for use by other sectors. The technology flow matrix captures these flows in a simple way. As an illustration, consider the example matrix in figure V.1. The elements of the first row of the matrix indicate how much R&D produced by industry 1 is consumed in any of the industries 1, 2, and 3. The diagonal elements of the matrix are approximations of the industry's own process R&D. The elements in any column indicate the amount of R&D that an industry receives from any of the other industries. Row sums are the total R&D originating in an industry, while column sums measure the total R&D consumption of an industry. In the example in Figure V.1, 34 units of R&D originate in industry 2, only 3 of which are used internally. The industry uses 12 units of R&D flowing in from other sectors.

Patents are used in this data construction effort to allocate an industry's R&D expenditures to a sector of use. Industry- and technology-based idiosyncrasies in patenting behavior will therefore not necessarily create a bias as long as the overall distribution of patents across sectors of use is not affected. Scherer (1984b) describes some of the problems that had to be solved in order to allocate R&D meaningfully to using sectors. The measure of total R&D use can be calculated under two alternative assumptions. If the R&D results produced in one sector and transferred to several other industries have public goods characteristics ("public goods assumption"), then all recipients are credited with the the origin industry's R&D expenditures weighted by a correction factor that reflects differences in the purchasing volume of the product embodying the R&D knowledge. Under the "private good" assumption, the R&D flows received by the using industries add up to the origin industry's R&D expenditures. Scherer calculated both data series for over two hundred industries.

A particularly difficult problem is the allocation of R&D to own process improvements. It is reasonable to assume that process innovations are often not patented and instead protected by secrecy. This would lead to a downward bias in the ratio of patents indicating internal use of R&D resources. But comparing his estimates to those of two alternative data sources (McGraw Hill research and development expenditure surveys and the PIMS data base of the Strategic Planning Institute), Scherer finds no evidence that the process R&D share measures are seriously biased.[6]

Scherer's results suggest that there is considerable variation in the ratio of R&D produced to R&D consumed. Sectors like lumber and wood products, ferrous metals, textiles, and apparel and leather are characterized by low origin to use ratios. Conversely, industries like farm machinery, computers and office equipment, construction and mining machinery, or instruments produce several times as much R&D than they consume. Results very similar to these are provided by Pavitt (1984), who uses data on about 2000 significant innovations introduced in the British industry between 1945 and 1979 to analyze sectoral patterns of innovation. For each innovation, he identifies the sector in which the innovation originated, the sector of final use, and the sector of the firm's principal activity. As in Scherer's work, the interindustry technology flows can be identified, though their measurement is now based on the number of significant innovations rather than expenditure-weighted patent counts. Based on his data, Pavitt proposes a taxonomy of three distinct patterns of innovation: supplier dominated innovation, innovation that largely depends on large-scale production, and science-based innovation.

Pavitt suggests that innovation in industries like agriculture, construction, textiles, lumber, wood and paper mill products, and printing and publishing originates mainly with suppliers of equipment and materials. Firms in the respective sector make only minor contributions to their own product and process technology. According to Pavitt, these firms tend to be small and have only limited internal R&D capabilities. Conversely, production-intensive firms operate on the basis of large-scale technologies that allow for considerable economies of scale. But these economies are "latent", i.e. they do not emerge automatically, but are achieved at the cost of internal efforts which are often undertaken by specialized production engineering departments.[7] Innovation in scale-intensive sectors may also originate with relatively small and highly specialized input suppliers (e.g. for instrumentation or process equipment). Finally, Pavitt identifies "science-based" sectors in which firms rely heavily on their own R&D efforts which are closely linked to progress in underlying sciences like chemistry, biology, or physics (among others). A recent example of such a sector is the emerging biotechnology industry in which several new enterprises were founded by university researchers.

The contributions by Scherer and Pavitt are noteworthy for several reasons. Both use samples from different countries and different underlying measures for innovative output. Nonetheless, a number of patterns detected in their data are remarkably similar. Both studies provide some support for the notion that R&D results are embodied in an industry's output and that buyers can often enjoy considerable benefit spillovers due to imperfect appropriability by firms in the producer industry. Furthermore, the sectors identified as net users or net producers of innovative technology match each other closely.[8] But it is also clear that the precise measurement of these effects is a difficult matter.[9] Furthermore, the determinants of the interindustry technology flows described by Scherer and Pavitt are still poorly understood. For many practical purposes, the descriptive account of technology flows proves immensely helpful and sufficient. But it is of great theoretical interest to probe deeper and explore the *endogenous* determination of these flows.

One way to approach this question is to explore the interdependence between R&D incentives of firms in vertically related industries.

Farber's (1981) study is to my knowledge the only recent empirical effort to shed some light on this problem.[10] Farber analyzes the effect of buyer market structure on the R&D incentives of seller industries and considers several effects of buyer market structure on the seller's rent expectations, e.g. the magnitude of rents, their appropriability, and the speed of adoption of technologies in the buyer industry. Using a model originally developed by Demsetz (1969), Farber suggests that the magnitude of innovation rents is greater if the buyer market is more monopolistic. With respect to appropriability and speed of adoption, he argues that increased concentration on the buyer's side is likely to discourage seller R&D efforts, in particular if the seller market itself is competitive. Farber's main argument is based on the notion that price discrimination is facilitated in settings where few sellers face many buyers. Farber then estimates a simultaneous equations system for R&D intensity (measured as employment of engineers and scientists divided by total employment), advertising intensity, and seller market concentration. Buyer market concentration is measured as the sales-weighted average of the four-firm concentration ratios of the industries the seller industry is supplying to. Farber's estimation results indicate that both buyer and seller market concentration have a strong and significant negative effect on the seller industry's R&D efforts. The interaction between these two variables, however, is positive and highly significant. Taken together, these results indicate that the sellers' R&D activity increases with buyer market concentration when the seller market itself is concentrated, but that it decreases with buyer concentration when the seller market is fragmented.

While these econometric results are suggestive, they *only* inform us about the effect of vertical organization on the seller's R&D activities.

Williamson's (1975, p.204) discussion of R&D incentives provides an alternative explanation of Farber's econometric results. Williamson describes conditions under which the burden of conducting R&D may be shifted from small suppliers to large established buyers in the vertical chain, but the logic of his argument can easily be applied to the interaction between large sellers and small buyers. "Market thinness" (high concentration) and barriers to entry in the buyer industry (e.g. created by first-mover advantages) will, according to Williamson, limit the rents that an upstream innovator can obtain from selling its technology to downstream firms. The lack of appropriate incentives will then lead to a shift of R&D efforts in the vertical chain. Williamson's comments are explicitly based on the notion that the same R&D projects can be alternatively undertaken by either the supplier or the buyer. In his work, the incentive shift arises from the large firm's problem to commit itself to pay a "reasonable" price for the innovation.

The models developed in chapters III and IV have suggested that vertical organization should have an effect on R&D incentives even in the absence of price discrimination and commitment problems. The strategic appropriation incentives analyzed in chapters III and IV constitute a new set of arguments in favor of a relationship between vertical organization and R&D incentives. In the following sections I summarize various theoretical arguments and develop a set of hypotheses which are then tested in a cross-sectional regression framework.

V.3 Vertical Organization and Incentives for R&D - Hypotheses

In this section I first discuss three arguments that are of importance for the interaction between supplier and buyer R&D incentives. Several testable hypotheses are stated in terms of industry aggregates and then tested in a cross-section of lines of business. The first group of arguments (section V.3.1) is directly based on the models developed in chapters III and IV of the thesis. I discuss the structural conditions under which the use of a strategic appropriation mechanism is particularly attractive for supplier firms. The alternative explanations discuss the effect of vertical organization on appropriability (section V.3.2) and on supplier-induced dissemination of information produced by downstream firms (section V.3.3).

For several reasons, an empirical test of these hypotheses using cross-sectional industry data from very different industries is far from ideal.[11] Clearly, it would be preferable to use data from a set of industries with similar demand and technology characteristics and differing supply sector organizations. Unfortunately, data on such a quasi-experiment are not available at this point. One weakness of the standard cross-sectional data is that it is difficult to control for industry-specific determinants of R&D incentives. Though the empirical literature concerning research and development incentives has made considerable progress over the last years, it is still relatively difficult to account for factors like technological opportunity and appropriability of returns to R&D. However, the cross-sectional framework provides a convenient way for a preliminary test of the hypotheses described below.

V.3.1 Strategic Appropriation

In this subsection, I use the results of chapters III and IV to formulate hypotheses based on the strategic appropriation argument. In intermediate goods markets, oligopolistic suppliers may care more about the overall size of the market than would competitive suppliers under otherwise comparable circumstances. Enlarging the market size can yield quasi-rents even if prices for the suppliers' products cannot be raised, or if upstream competitors have relatively stable market shares. In order to focus on these incentives, let me assume in the following discussion that the pre- and post-innovation prices for the factor supplied by the upstream sector are indeed identical.

Upstream producers may then decide to to engage in activities that stimulate factor demand or prevent a restriction of demand growth. Three effects have been discussed in the preceding chapters. The first ("entry effect") implies that suppliers may seek to induce entry into their buyer industries. The desirability of the entry effect is contingent on the implications of entry for downstream R&D incentives and factor demand. As I showed in chapter III, the strategy may be profitable for suppliers even if downstream R&D incentives are reduced, since firms in the upstream sector may value downstream competition more than downstream innovation. The second effect ("cost reduction effect") implies that upstream producers may seek to lower downstream costs or enhance downstream product quality if their customers are not sufficiently engaged in these activities. The third effect ("preemption effect") may induce upstream firms to preempt downstream R&D activities in order to maintain a largely competitive structure in the downstream market. These three incentives arise only if the welfare of firms in the upstream sector is strongly tied to the extent of competition and innovation in the downstream sector, i.e. if the cost share of upstream producers in downstream production is high and if suppliers can demand a factor price above marginal cost. Since strategically induced changes in the downstream industry may represent a public good for the upstream sector as a whole, these strategic incentives are also likely to vary with the market share that upstream firms hold.

The suppliers' incentives for making strategic R&D investments are also contingent on conditions in the downstream sector. In the case of the entry effect, existing barriers to entry and sunk cost investments in the downstream industry are likely to reduce upstream incentives to engage in accommodation of new entrants.[12] I demonstrated in chapter III that existing sunk costs lower the effect of the upstream firm's R&D investment on downstream industry structure, even if one presumes that entry would take place instantaneously.

If entry into the downstream industry is slow or if exogenous barriers to entry exist, the upstream firms may still have strategic incentives to affect the degree of innovation in the downstream industry ("cost reduction effect")[13]. The incentives to do so are now guided by the return that a supplier can reap from promoting downstream innovation. A graphical illustration of the effect is sketched in Figure V.2. Assume that an upstream supplier can transfer a cost-reducing innovation to downstream firms. Furthermore, let the upstream firm's profit be an increasing function of downstream output as one could reasonably expect. The innovation reduces downstream costs from the ex ante level c to the ex post level c' so that $\Delta c = c - c'$. Consider first the case of a downstream monopoly or of a dominant firm.[14] The downstream monopolist will be able to restrict ex post output and the cost reduction will translate into a relatively small increase in output ΔQ_M. Conversely, in the case of a perfectly competitive downstream industry that adopts the supplier's technology, there will be no restriction on ex post industry output and the supplier enjoys the greatest possible increase in factor demand, denoted ΔQ_C in Figure V.2. Upstream incentives to induce a cost reduction effect will then be the stronger, the closer the downstream industry approaches the competitive ideal.

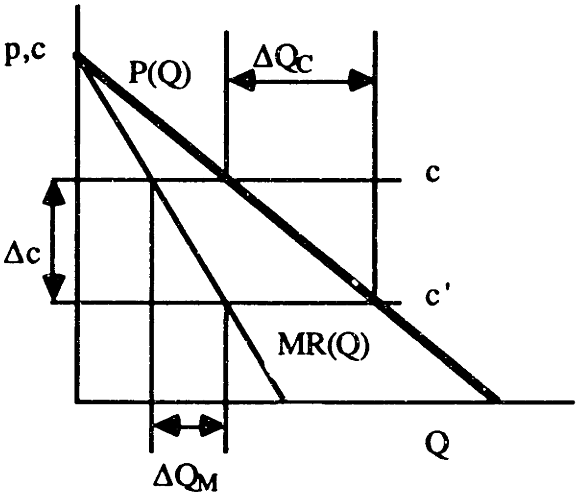

Figure V.2
Output Effect of a Cost-Reducing Innovation

A similar argument can be made in the case of upstream preemption incentives. Preempting downstream innovation is less profitable for suppliers if ex post the downstream industry will still be structured as a tight oligopoly. The reason is again that oligopolists will restrict output in some way to assure themselves a market price exceeding marginal cost.

All three effects then promise greater marginal returns to suppliers if the upstream industry is concentrated and if the downstream sector is fragmented. Summarizing these arguments I suggest the following hypothesis:

> Hypothesis 1) The research intensity of a fragmented buyer industry will be correlated negatively with the industry's dependence on concentrated supply sectors.

The discussion of interindustry technology flows suggested that these may be substitutes for flows of disembodied information. They may also lend themselves to be employed in a strategic appropriation mechanism. Technology flow measures that are based on patents may also contain some fraction of disembodied R&D that flows to a downstream sector. Since I have not modelled the effect of these flows in detail, I suggest here a tentative second hypothesis. If flows of embodied R&D have indeed an effect similar to that of spillover information, then they should reduce the R&D intensity of fragmented downstream sectors, but not necessarily the R&D intensity of more concentrated buyer sectors:

> Hypothesis 2) Technology flows into a fragmented buyer industry will be correlated negatively with the industry's R&D intensity.

Whether the technology flow variables and the structural variables measuring supply sector organization do indeed measure the same or a similar phenomenon should be visible in their performance in a regression analysis. The inclusion of the technology flow variable should weaken the coefficient of the structural measures if such an overlap exists, but it should leave the coefficient unaffected (or strengthen it) if the two variables capture different phenomena.

A cross-sectional test cannot demonstrate any causal direction. Therefore, statistical support for these hypotheses may reflect two possibilities: first, that the correlations hypothesized here are the consequence of strategic upstream behavior, or second, that the correlations are the consequence of upstream R&D efforts meant to compensate for ex ante weak downstream incentives. Both possibilities have a theoretical basis, as chapters III and IV demonstrated, but they cannot be distinguished here.

V.3.2 Price Discrimination and Excessive Appropriability

The second group of arguments discussed here focuses on the effect of vertical organization on an innovator's appropriability. Farber (1981) has suggested that oligopolistic suppliers will have comparatively greater power of price discrimination if they face a fragmented buyer industry. He concludes that price discrimination should allow innovators in the supply sector to reap greater quasi-rents for their innovations, and thus promote upstream R&D incentives. Farber's argument is essentially an application of the countervailing power hypothesis[15] to a study of R&D incentives. Since greater appropriability via price discrimination will affect R&D expenditures in a positive way, Farber tests his suggestion using upstream R&D intensity as the dependent variable and finds the expected result confirmed in a cross-sectional regression study.

Farber does not comment on the effect that upstream price discrimination might have on innovative activity in downstream sectors. Whether such an effect should exist or not depends on how price discrimination is implemented in particular pricing strategies. Ideally, the upstream producers would like to leave downstream incentives for R&D intact, since downstream R&D may impose a positive externality on the upstream sector.[16] Extraction of quasi-rents will then have no effect on R&D expenditures, sales, and the ratio of these two, R&D intensity.

But even if downstream R&D incentives are distorted, this effect will in all likelihood not be visible in the downstream industry's R&D intensity. If upstream suppliers can discriminate and ask some buyer for higher prices than they would be paying under a linear pricing schedule, production costs will be higher for these firms. Theoretical models suggest that a higher level of downstream production costs will cause a reduction in downstream R&D incentives.[17] However, higher input prices will also depress sales, so that that R&D intensity (defined as R&D expenditures over sales) will not necessarily change or only through a second-order effect with ambiguous direction.[18] This is of course one of the virtues of this measure, and a reason why it has been so popular in empirical analyses.

Upstream price discrimination per se is therefore unlikely to affect downstream *R&D intensity*. This result does not imply that there cannot be a socially detrimental disincentive effect. Clearly, both downstream industry output and R&D expenditures may be reduced in the presence of effective price discrimination by suppliers. As I noted in chapter III, upstream appropriability may actually be too strong even from the supplier firms' point of view. The optimal pricing policy of a supplier may require a credible commitment to charge a relatively low price in the future. If suppliers do not have the capability to restrict their own future behavior in a credible way, downstream producers may reduce their R&D efforts. As a *consequence* then, the supply sector may have to engage in R&D efforts that compensate for the lessened downstream incentives. This is in essence an extension of Williamson's (1975) argument. Excessive appropriability and commitment problems can lead to a shift of R&D activities from the downstream to the upstream sector. Furthermore, if upstream R&D then enhances downstream output (even without reducing downstream R&D expenditures), the downstream R&D intensity will be lowered.

These are of course also the circumstances for which the strategic appropriation argument predicts a reduction in downstream R&D intensity. These two groups of hypotheses cannot be distinguished perfectly at this point, since both imply lower downstream R&D intensity under identical structural conditions and an inflow of technology that is negatively correlated with R&D intensity.

V.3.3 Intraindustry Spillovers and Protection Efforts

Supplier behavior can be an important determinant of the rate of intra-industry spillovers experienced by firms in the buyer industry (Corey 1956; Mishina 1989). Even the anticipation of information dissemination by suppliers can lead to inefficient R&D investments in the downstream industry. Suppliers may actually not want to promote downstream spillovers, depending on the effect that these spillovers have on downstream R&D incentives and on the demand for the supplier's factor of production. But even if suppliers find it against their long-term interest to promote greater spillovers, they may face a commitment problem in that they cannot credibly commit to nonopportunistic behavior.

For a number of reasons, supplier firms are often in a privileged position to observe the technological activities of their customers. Suppliers can often observe which, and in what proportion, inputs are used in downstream production. Moreover, they often offer technical services at the downstream production site and may therefore have privileged access to production plants. Cooperative R&D between suppliers and their customers often involves the exchange of information and raises the prospect of information spillovers. In some chemical industries, upstream suppliers can be held liable if their intermediate goods cause environmental hazards in downstream production (e.g. in the semiconductor industry). The suppliers therefore seek to protect themselves by imposing handling restrictions and other prescriptive measures on downstream producers. These measures are often enforced by plant audits during which the supplier representative may also learn about novel technologies in the customer's plant.

The hypothesis that suppliers may be able to increase the rate at which knowledge spills from one buyer firm to another is also supported by the observation that firms often try to prevent suppliers from getting a close look at their production facilities (Corey 1956). If such protection is imperfect, suppliers may be able to collect important information and promote the diffusion of downstream innovations. It may suffice that suppliers appear to behave opportunistically if they cannot commit to benevolent behavior, or if downstream firms have no means to impose penalties if information is leaked via the supplier. Commitment problems are particularly troublesome in settings where few upstream firms face many downstream buyers. Presumably the upstream ability to gather information is particularly strong in this case. If contracts are only imperfect instruments to commit to benevolent behavior (Williamson 1975), then the degree to which downstream firms will fear opportunistic behavior may also depend on their own capability to detect and punish a breach of trust. Both detection and punishment are likely to be more costly if the downstream sector consists of numerous small entities which face large supplier firms. Absent a credible check on opportunistic behavior, investment decisions are likely to be inefficient.[19]

I argued above that upstream suppliers have greater incentives to promote downstream cost reduction if the buyer sector's pricing behavior is characterized by small margins. Furthermore, if there are free-rider effects across suppliers, then these incentives will be comparatively stronger in the case of a tight upstream oligopoly. Promoting downstream spillovers can be seen as the transfer of an innovation from the supplier to downstream firms. Hence, both in terms of upstream incentives and downstream capabilities to prevent opportunistic behavior, it is likely that downstream R&D incentives will be distorted if oligopolistic suppliers face a fragmented buyer industry. Suppliers may again be forced to compensate for the weakened R&D incentives in the buyer industry. This argument then suggests the same hypotheses as stated in the previous subsection.

However, we can hypothesize a second effect here concerning the protective efforts that downstream firms will undertake to avoid spillovers. If a firm has produced proprietary information, then it usually faces several alternative means of protecting its intellectual property. Two alternatives are of particular importance here: trade secrets and patent protection. It has often been argued that in the case of process innovations, firms in many industries will prefer trade secrets as a protection mechanism (Cohen and Levin 1989). This presumption is based on two arguments. First, applying for a patent may reveal important information to competitors who can "invent around" the original patent. Second, it may be very difficult to monitor patent violations since process technologies are usually not observable by outsiders. The latter argument also speaks in favor of protecting own process technologies by trade secrets. In the case of process innovations this should shift the tradeoff between the two protection mechanisms in favor of trade secrets.

Consider now an industry in which suppliers can to some degree observe process technologies and may have an incentive to disseminate the respective information. The very advantage of trade secrets - nonobservability by outsiders - is lost to some degree. Hence, if downstream firms are constrained in their means to control upstream behavior, they may be inclined to revert to stronger patenting efforts. This suggests the following hypothesis, again formulated for an industry level analysis:

> Hypothesis 3) The patenting propensity of a fragmented buyer industry will be correlated positively with the industry's dependence on concentrated supply sectors.

This hypothesis simply states that patent propensity (measured as patents per R&D dollar) should be higher if downstream firms are concerned about the vertical spillover channel. A firm's patenting propensity is interpreted here as an indicator of innovative output and of protection efforts while most patenting studies focus purely on the first aspect of patent ownership.

V.4 Empirical Specification

V.4.1 Data Sources and Specification

Data Sources

The data used here are taken from the 1976 FTC Line of Business Database and from the 1977 input-output tables of the United States economy. This time difference should not be a major concern, since changes in input-output structures over such a short period tend to be fairly small. The technology flow variables are based on Scherer's (1984b) study. The patent data were also compiled by Scherer, and a description of the data is given in Scherer (1983). I also make use of survey data which are often referred to as the Yale survey and described in Levin et al. (1987). (To identify these survey variables in the subsequent discussion, I will use the superscript character ^{Y}, for Yale survey.) A summary of variables and data sources is provided in the appendix (Table V.A.1). Sample statistics of the dependent and independent variables are summarized in the appendix in Table V.A.2. The empirical specifications are described in the next subsections, followed by the estimation results.

Combining data from several sources in a test of this form is not without problems. While the Yale survey was designed to be used in conjunction with the FTC data, I had to match the input-output (SIC classifications) to the corresponding FTC data. Such a matching procedure is common practice in cross-sectional analyses of R&D intensity, but it may nonetheless introduce an errors-in-variables problem. The use of Scherer's patent data together with the FTC data should not be problematic, since this dataset on technology flows was created by using the FTC's information on R&D expenditures.

The R&D Equation

Since structural models may impose undue constraints on the estimation results (Cohen and Levin 1989, p. 1085), I model an industry's R&D intensity (RS) here as a linear function of dependent variables.[20] Only company-financed R&D is included in the R&D variable, since the incentives and opportunities to perform government-funded R&D or other contracted R&D work pose a problem in their own right.[21]

I approximate the right-hand side of the regression equation as a linear function of independent variables. The independent variables fall into four broad categories. A short summary is presented here, and exact definitions are provided in the appendix. The first three categories (demand, appropriability, and technological opportunity) follow closely the variable definitions used in a recent empirical investigation by Cohen and Levinthal (1989).[22] However, the present analysis is somewhat more limited in degrees of freedom, since I only use the FTC data aggregated by line of business, while Cohen and Levinthal employed the same dataset at the firm level. The fourth group of explanatory variables captures the effect of vertical organization on R&D intensity.

Demand conditions are controlled for by measures of price elasticity (PELAS), income elasticity (INCELAS) and an industry growth rate (GROWTH). These measures were calculated from the 1970 and 1977 input-output tables by Levin (1981). While industry growth and income elasticity should affect research intensity positively, the sign of the coefficient of price elasticity is ambiguous. An aggregate measure of appropriability ($APPR^Y$) and imitation lag time for a product innovation ($IMLAG^Y$) is also included among the independent variables. These measures are derived from the survey conducted by Levin et al. (1983). I have to assume here that appropriability conditions have remained fairly stable between 1976 and 1983. This assumption has been made implicitly in a number of studies using the appropriability variables from the Yale survey (Cohen and Levinthal 1990a; Levin and Reiss 1988), but it constitutes a conceivable weakness of these variables when used in conjunction with 1976 R&D data.

It is also common practice in this literature to use measures of "technological opportunity" to control for inter-industry differences. I have already commented in chapter III on conceptual problems with these variables and use them here primarily as controls. The measures are supposed to capture the closeness of an industry to sciences, the contributions of other sectors to technical change in the industry, and the maturity of the industry. The Levin et al. (1987) survey data have become the standard data source for these variables, but due to the small sample size of 120 lines of business I can only include a limited number of these. However, since previous analyses are available I can aggregate variables, for example by relying on some of the Cohen and Levinthal results.[23]

Greater relevance of sciences related to the industry's technological base may necessitate the allocation of R&D resources that are not required in an industry where the underlying scientific and technical relationships are well-established and mature. The existence of science-based knowledge may encourage the building of internal R&D capabilities precisely for the reason to absorb and utilize the external knowledge, as Cohen and Levinthal (1989) have suggested. External scientific knowledge may also affect the marginal cost of R&D and thus lead to increased utilization of R&D resources. But the effect of "closeness to sciences" is ambiguous ex ante. Besides having a positive effect on a firm's R&D investment, greater relevance of scientific disciplines may also result in new information that serves as a substitute for internally produced knowhow and can thereby cause a reduction in R&D efforts. Cohen and Levinthal (1989) study the relevance of eleven basic and applied scientific disciplines on R&D investments and find that most of them are positively correlated with R&D intensity at the firm level. I define as SCIENCE1^{Y} the average relevance of all disciplines that yielded a positive effect in the Cohen/Levinthal study (i.e. biology, chemistry, mathematics, physics, computer science, materials science, and medical science). $SCIENCE2^Y$ is defined as the average relevance of disciplines with a significant negative effect (agricultural science, applied mathematics and operations research, geology, and metallurgy) in the Cohen/Levinthal study. This procedure is admittedly heuristic, but it offers the advantage of economizing on degrees of freedom while maintaining relevant control variables. (As an alternative one could use a factor analysis approach, but the results would certainly be even more heuristic than the method used here.)

Several external sectors may contribute to technical change in an industry. To control for the effect that R&D embodied in capital equipment may have, I follow Cohen and Levinthal and include in the regression analysis a measure of contributions by upstream suppliers of production and research equipment ($EQSUP^Y$). As an indicator for downstream contributions originating with users of the industry's output, I include the variable $USERS^Y$. As von Hippel (1988) has pointed out, users of a product are in many industries at least a source of innovative ideas and often even the first to build prototypes of innovative products. However, Cohen and Levinthal note correctly that the variable may also reflect the degree of product differentiation in the industry, so the interpretation of its coefficient is somewhat ambiguous.

Government agencies and laboratories and universities may also affect an industry's R&D intensity, since they constitute sources of external knowledge with either complementary or substitute character. The variable used here (GOVUNIV) is the average of $GOVTECH^Y$ and $UNIVTECH^Y$ as used by Cohen and Levinthal. These two measures were again derived from the 1983 questionnaire survey conducted by Levin and associates.[24]

Finally, the age of the industry's capital stock may have a significant effect on the extent of R&D efforts in comparison to industry sales (Levin, Cohen et al. 1985). The FTC data include a measure of an industry's percentage of property, plant, and equipment installed within the five years preceding 1976. This measure (NEWPL10) is included in all of the regressions presented below. Again, consistent with previous results, I expect a positive effect, since the newness of production lines is supposed to be positively correlated with activities like "debugging", "debottlenecking", etc.

Testing the hypotheses developed in section V.3 requires an operationalization of the supply industry's characteristics. The supply sector variables used here only capture the possible influence of intermediate goods producers (components, materials, etc.).[25] A simple measure of supply sector organization is the sum of cost shares of intermediate inputs weighted by the respective supply sector's four-firm concentration ratio (WSH for weighted factor shares).[26] I computed this measure from the 1977 input-output tables and census information on industry structure.[27] Any intermediate inputs that were produced by the industry itself (secondary production) were excluded from these calculations. The reason for this exclusion is that vertical integration into the production of these inputs would lower the dependence of the downstream industry on upstream supplies.

The aggregate measure of supply sector organization (WSH) can be an ambiguous characterization of a given industry, since very different supply sector structures can be characterized by the same value of WSH. To circumvent this problem I also constructed a second measure that groups supply sectors into two categories according to their four-firm concentration ratio. Supply sector organization is characterized by the cost share of intermediate inputs supplied by industries with a four-firm concentration ratio of smaller than forty-five per cent, and by the cost share of inputs supplied by industries with a four-firm concentration ratio of greater than forty-five per cent (SH45).[28] These measures neglect the differences between industries allocated to the same group. Since both of the latter two measures are perfectly collinear, only the factor cost share supplied by the high concentration category (SH45) is included in the regressions.

Finally, I use technology flow measures based on Scherer's (1984) study in which he linked R&D expenditures to patents and determined the industry in which the respective technology was applied. From his data I computed a measure of the amount of R&D flowing into an industry from external sources, defined as the difference between the total R&D used by the industry (RDUSE) minus the amount of own R&D spent on process innovations. In terms of the example matrix in Figure V.1, this measure consists of the column sums minus the diagonal elements in the flow matrix. This indicator is divided by the receiving industry's sales in order to construct a measure analogous to the R&D intensity of the industry. Since Scherer computed the matrix both under a public goods and a private goods assumption, I use both technology flow measures (EXTERN1, EXTERN2) to test the robustness of the empirical results.

The regressions include the measures of supply sector organization and interaction terms necessary to identify relevant subsamples in which a substitution effect between upstream and downstream R&D is either likely or not likely to occur. Since these interaction terms utilize the four-firm concentration ratio (which is presumably endogenously determined with the dependent variable), they are conceivably correlated with the error terms of the R&D regressions. To avoid the bias arising from simultaneity I also estimate the R&D equation using instrumental variables (IV) estimators.

The Patent Equation

The patent equation follows in principle previous work by Bound et al. (1984), Pakes and Griliches (1984), Scherer (1983), and Jaffe (1986) . A recent survey of the patenting literature is presented by Griliches (1991). However, patents are not exclusively treated as an indicator of innovative output here, but also as one particular instrument of protecting intellectual property. The hypothesis to be tested here states that under certain forms of vertical organization, patenting is more likely to be the protection mechanism of choice.

In addition to the total number of patents (PATENTS) granted to firms in a given industry I also use a second dependent variable, the total number of claims statements contained in the patents (CLAIMS).[29] Using this variable may compensate to some degree for the heterogeneity across patents. The presumption is that patent applicants who seek strong protection may want to increase the number of claims stated in the patent and thus achieve a stronger protection of their intellectual property.

Some complications arise because both patents and claims are positive count variables so that a standard OLS framework is likely to produce biased estimation results. Empirical studies have usually circumvented this problem by using extended log-linear specifications, nonlinear least squares, or distributional assumptions that explicitly take the properties of the dependent variable into account.[30] Since zero patent or claim counts did not occur in this highly aggregated sample, I follow Jaffe's suggestion and assume that the relationship between industry patent count PATENTS and independent variables is given by $\text{PATENTS} = \exp\{\Sigma X_i\beta_i\} \exp\{v\} R$. The row vectors X_i denote here the independent propensity variables, v is an independently and normally distributed error term, and R indicates the total R&D expenditures of the industry. This assumption is of particular convenience, since transformation to a logarithmic form leads to the specification log PATENTS $= \Sigma X_i \beta_i + \log R + v$, which can be estimated in the standard linear regression framework. The same argument applies to the CLAIMS relationship. Following Scherer (1983), I also include among the right-hand side variables the logarithm of industry sales in order to control for possible nonlinearities in the relationships. Idiosyncrasies in patenting behavior are partially accounted for by a number of technology technology group variables (DELECT, DMECH, DCHEM, DFOOD, DINST). These dummy categories are subjective, but were created prior to performing the statistical test. I also include the two science indicators (SCIENCE1^{Y}, SCIENCE2^{Y}) known from the R&D equation to rule out other types of spurious correlations. The Yale survey provides additional measures on the effectiveness of patents (PAPPR1^{Y}, PAPPR2^{Y}, PAPPR3^{Y}, PAPPR4^{Y}) and the innovator's lead time before imitators can "invent around" a patent (IMLAG^{Y}). These measures should jointly reflect the relative strength of patenting over trade secrets, lead time, and other protection mechanisms. Finally, I include the industry's concentration ratio (C4), a measure of supply sector organization (SH45 or WSH10) and the interaction of the supply sector measure with the industry's own concentration ratio (SH45*C4 or WSH10*C4). The supply sector variables were already described in the discussion of the R&D equation.

V.4.2 Estimation Results

The R&D Equation

The results of the regressions following the simple linear model are presented in Tables V.1 and V.2. Table V.1 presents least squares results, while Table V.2 compares the ordinary least squares estimate for the full model to nonlinear two-stage least squares estimates. The heteroskedasticity-robust variance-covariance estimator proposed by White (1980) is used in all regressions, since Breusch-Pagan tests on the benchmark specification (R1) indicate the presence of heteroskedasticity. Heteroskedasticity-corrected OLS results are denoted by OLS-H, while the instrumental variables estimators (also using the White correction) are denoted 2SLS. The sample consists of 120 lines of business for each specification, i.e. it is limited to Levin's subset of the FTC sample.

Since both supply sector variables WSH10 and SH45 produced very similar results, I present only estimates using the SH45 measure. Due to the small sample size, some coefficients have fairly large standard errors, but most results appear to be consistent with those obtained by Cohen and Levinthal. The coefficients on price and income elasticity (PELAS and INCELAS) are highly significant in the OLS specifications and have the same sign as in the Cohen/Levinthal study. The coefficients for GROWTH and $APPR^{Y}$ are positive, but insignificant in all specifications. They are therefore not reported in the two tables. This result is not completely unexpected for the appropriability variable $APPR^{Y}$. Statistical shortcomings of this variable have been discussed before and are probably due to problems in the survey instrument used by Levin et al.[31] The imitation lag variable ($IMLAG^{Y}$) only becomes significant after the supply sector and technology flow variables are included among the independent variables.

Table V.1

Dependent Variable: RS

	OLS-H	OLS-H	OLS-H	OLS-H	OLS-H
	(R1)	(R2)	(R3)	(R4)	(R5)
CONSTANT	-3.512*	-3.750**	-3.174*	-3.154*	-2.440
	1.853	1.858	1.723	1.733	1.606
PELAS	-0.234**	-0.217**	-0.181**	-0.218***	-0.180**
	0.094	0.085	0.079	0.077	0.074
INCELAS	1.379***	1.327***	1.366***	1.305***	1.352***
	0.310	0.296	0.296	0.296	0.267
IMLAG	0.199	0.160	0.206	0.243**	0.294**
	0.121	0.125	0.126	0.115	0.115
SCIENCE1	0.677**	0.657**	0.496*	0.549**	0.370
	0.278	0.271	0.287	0.252	0.262
SCIENCE2	-0.568***	-0.631***	-0.553***	-0.640***	-0.557***
	0.174	0.168	0.169	0.166	0.167
EQSUP	-0.352**	-0.355**	-0.387***	-0.388***	-0.417***
	0.137	0.136	0.137	0.131	0.130
USERS	0.345***	0.393***	0.426***	0.353***	0.391***
	0.130	0.142	0.145	0.131	0.133
GOVUNIV	0.469***	0.486***	0.478***	0.494***	0.475***
	0.163	0.158	0.156	0.151	0.144
NEWPL10	0.323**	0.338**	0.363**	0.322**	0.349**
	0.161	0.157	0.154	0.156	0.154
C4		0.012*	-0.002	0.0007	-0.015
		0.006	0.010	0.007	0.010
*SH45*C4*			0.068*		0.069**
			0.037		0.028
SH45			-4.036**		-4.329***
			1.676		1.367
*EXTERN1*C4*				0.024***	0.026***
				0.008	0.008
EXTERN1				-0.573**	-0.653**
				0.287	0.291
N	120	120	120	120	120
S.E.E.	1.353	1.339	1.327	1.300	1.281

Note: standard errors are printed below the coefficients. The coefficients for the GROWTH and APPR variables are not included in this table. Both coefficients were positive but insignificant in all specifications.

*	significant at the .1 level (two-tailed test)
**	significant at the .05 level (two-tailed test)
***	significant at the .01 level (two-tailed test)

Table V.2
Dependent Variable: RS

	OLS-H (R5)	2SLS (R6)	OLS-H (R7)	2SLS (R8)
CONSTANT	-2.440*	0.107	-2.836*	-1.054
	1.606	1.518	1.678	1.828
PELAS	-0.180**	-0.124	-0.157**	-0.016
	0.074	0.094	0.076	0.126
INCELAS	1.352***	1.343***	1.366***	1.449***
	0.267	0.313	0.296	0.334
IMLAG	0.294**	0.428***	0.238**	0.342**
	0.115	0.130	0.119	0.141
SCIENCE1	0.370	0.364	0.431	0.167
	0.262	0.323	0.273	0.395
SCIENCE2	-0.557***	-0.644***	-0.558***	-0.590**
	0.167	0.193	0.168	0.226
EQSUP	-0.417**	-0.286*	-0.366***	-0.265
	0.130	0.161	0.132	0.184
USERS	0.391***	0.442***	0.431***	0.525***
	0.133	0.148	0.145	0.175
GOVUNIV	0.475***	0.189	0.444***	0.238
	0.144	0.204	0.144	0.239
NEWPL10	0.349**	0.322*	0.358**	0.322*
	0.154	0.164	0.155	0.179
C4	-0.015	-0.075***	-0.015	-0.075**
	0.010	0.023	0.011	0.028
*SH45*C4*	0.069**	0.082*	0.061**	0.029
	0.028	0.044	0.029	0.058
SH45	-4.329***	-5.613**	-3.673**	-1.633
	1.367	2.332	1.437	3.437
*EXTERN1*C4*	0.026***	0.113**		
	0.008	0.043		
EXTERN1	-0.653**	-4.300**		
	0.291	1.896		
*EXTERN2*C4*			0.005**	0.024**
			0.002	0.010
EXTERN2			-0.156***	-0.936**
			0.058	0.448
N	120	120	120	120
S.E.E.	1.281	1.650	1.322	1.687
		χ^2=10.84		χ^2=13.08

Note: standard errors are printed below the coefficients. The coefficients for the GROWTH and APPR variables are not included in this table. Both coefficients were positive but insignificant in all specifications. The χ^2 statistic for the overidentification test is the sample size multiplied by the R^2 obtained from regressing the residuals on the instruments (Hausman 1983).

The point estimates for the two variables measuring the relevance of various scientific disciplines also carry the expected sign. Both SCIENCE1^{Y} and SCIENCE2^{Y} appear to have strong effects on R&D intensity. But only the SCIENCE2^{Y} variable is significant throughout all specifications, while the effect of SCIENCE1^{Y} is weakened once the supply sector and technology flow variables are included. Nonetheless, the separation of the two science variables according to prior regression results has a clear payoff here, since the control for the effect of scientific disciplines is far better than with inclusion of only one aggregate variable.

Greater contributions by equipment suppliers (EQSUP^{Y}) tend to reduce an industry's R&D intensity. This phenomenon may occur for two reasons. First, the industry's own R&D efforts may be significantly lower if equipment suppliers offer capital goods that are substitutes for an industry's own R&D efforts. Second, the contributions by equipment suppliers may simply enhance the productivity of the downstream sector without affecting the buyer firms' R&D decisions. This explanation is somewhat less plausible, since productivity enhancements should also affect the marginal productivity of the industry's own R&D and thus lead to greater R&D investments.

Since the supply sector variables only capture the effect of intermediate input suppliers, but not of capital goods suppliers, it is not surprising that the coefficient on EQSUP^{Y} does not change dramatically once the variables measuring supply sector structure are included. However, one should expect that the inclusion of technology flow variables (EXTERN1 and EXTERN2) would weaken the equipment supplier variable. This is apparently not the case in the simple specifications without endogeneity correction in table V.1. Since the flow variables are based on patent statistics, it is conceivable that the survey variable EQSUP^Y and the flow measure capture largely independent aspects of technology flows and contributions to technical change.

The contributions by USERS^Y appear to complement R&D efforts within an industry. The coefficients for this variable are extremely stable and in all specifications significant at the .01 level (two-tailed tests). But this variable is also likely to capture the effect of product differentiation: industries that produce custom-tailored goods are likely to do more R&D in order to produce for relatively specific requirements. External contributions from government laboratories and agencies and from universities are also clearly identified by the regressions. Finally, the percentage of "new" plant, property, and equipment (NEWPL10) is positively correlated with the industry's R&D efforts. These two coefficient signs are expected and also consistent with the Cohen/Levinthal results.

The hypothesis to be tested here concerns the effect of the supply sector and technology flow variables. As predicted, the coefficients of the supply sector and flow variables themselves carry negative signs, while the interaction terms between these variables and the industry's own concentration are always positive.[32] In the simple OLS estimations (e.g. in (R5)) there appears to be no tradeoff between the effects of these two variables. Including both in regression (R5) actually strengthens both estimates. Note also that the concentration variable itself does not appear to play any significant role in these OLS regressions. This is not surprising, since the control variables themselves are likely to explain a considerable portion of the variance contained in the concentration variable. Nonetheless, the results suggest that industries with high and with low concentration appear to react quite differently to the presence of "strong" supply sectors. In the case of fragmented sectors, the presence of oligopolistic supply sectors is clearly correlated with reduced R&D intensity.

Similarly, greater inflows of R&D as measured by Scherer's indicator appear to have a negative effect on the R&D intensity of fragmented downstream sectors while the result is reversed for highly concentrated ones. It is noteworthy that in the simple specifications in table V.1 there is apparently no trade-off between the variable measuring supply sector structure (SH45) and the measure of interindustry technology flows (EXTERN1). Comparing the results of specification (R3) to those of (R7) in table V.2, it turns out that including the second technology flow variable (EXTERN2) and the respective interaction term (EXTERN2*C4) weakens the supply sector variable only slightly. Based on these results, one would come to the conclusion that the coefficients for the flow variables and the coefficient for the indicator of supply sector structure reflect largely independent phenomena.

These results seem to provide consistent and strong support for the suggestion that vertical organization exerts a strong effect on R&D incentives. One would be concerned, however, that the use of the concentration variable could cause a bias, since it may be determined endogenously. Similarly, the inflow of technology (measured by EXTERN1 and EXTERN2) is conceivably determined simultaneously with the R&D intensity in the downstream industry. Indeed, the model developed in chapter III predicts a simultaneous determination of upstream and downstream R&D incentives. The specifications presented in Table V.2 address these concerns regarding a possible simultaneity bias. Regressions (R6) and (R8) are based on a nonlinear two-stage least squares specification. R&D intensity is assumed to be endogenously determined with market structure and technology inflows. The instruments used here include all exogenous and predetermined variables, i.e. all independent variables with the exception of the four-firm concentration ratio and the technology flow measures. Furthermore, I followed Farber (1981) and used as instruments measures of minimum efficient scale, capital requirements, and the predetermined value of the concentration ratio in 1972. To identify the technology flows, I also included six industry classification variables (DCHEM, DELEC, DMACH, DINST, DMETAL, DFOOD) as instruments. Identification of the nonlinear model was also facilitated by using nonlinear combinations of the instruments (Hausman 1983). The need to estimate a nonlinear relationship arises here because the endogenously determined variables enter the equation both linearly and as factors in interaction terms. The results in (R6) can be directly compared to the OLS results in (R5). As one should expect, the reduced efficiency of the instrumental variable estimator causes standard errors to be somewhat larger throughout. The interaction terms maintain a positive sign, while the SH45 and EXTERN1 variables again have a negative sign. Apparently, the instrumental variables estimation has the strongest effect on the technology flow coefficients. The coefficients for EXTERN1 and the interaction term in specification (R6) are substantially large than in the simple least squares model. The overidentification test does not lead to a rejection of this specification since I cannot reject the overidentifying restrictions at the .1 level. Estimating R&D intensity, industry structure, and technology flows under the private goods assumption (EXTERN1) endogenously supports the conclusions derived from the OLS results.

The endogeneity correction has an interesting effect on the coefficients of some of the control variables. The coefficient of EQSUP^{Y} (measuring the contributions to downstream innovation made by equipment suppliers) is barely significant in specification (R6) and (R8) and considerably smaller than in the simple least squares estimations. The four-firm concentration ratio becomes significant at the .05 level and is negative in both 2SLS-specifications. Finally, the imitation lag variable is significant at the .05 level in (R6) and (R8) and considerably larger than in the OLS specifications. However, none of these differences between 2SLS and OLS estimates is large enough to reverse any of the conclusions discussed above.

If the flow measures computed under the public goods assumption are used, another interesting result emerges from the two-stage estimation in (R8). The supply sector variables which are significant in the OLS specification (R7) become insignificant and smaller in size, while the flow variable and its interaction term with industry structure remain significant and are larger then in specification (R7). This result on its own would suggest that the technology flow variable EXTERN2 has a stronger explanatory effect than the measures of supply sector structure. Indeed, regressing EXTERN2 on the structural variable SH45, the interaction term SH45*C4, and industry concentration demonstrates a strong relationship, with SH45 being positive and significant at the .05 level. The interaction term is negative and significant at the .1 level. This result is puzzling because the EXTERN1 variable shows no apparent trade-off with the measures of supply sector structure. The observation that the flow measure EXTERN2 reduces the supply sector indicators to insignificance could be explained if the weighting scheme used by Scherer (1984b, pp. 432-435) to derive this variable is correlated with the factor share structure for any given buyer industry. However, one would expect this correlation to show up in specification (R7) as well. A less systematic explanation may come from the observation that the flow measures based on the public goods assumption were only weak predictors of productivity growth (Scherer 1984b, p. 449). Since calculating the flow measures under the public goods assumption required a complex set of assumptions, the quality of the EXTERN1 variable may simply be superior to that of the public goods measure EXTERN2. Since the size of the sample used here imposes constraints, it may be possible to solve this problem in future work by using the full FTC sample with around 270 industries. Using the larger sample would also provide a basis for using more powerful specification tests.

With the exception of these conflicting findings in equations (R6) and (R8), the results support the first two hypotheses derived in section V.3. But given the cross-sectional nature of the sample it is not possible to test whether it is strategic behavior by upstream suppliers, excessive upstream appropriability, or supplier-induced spillovers that lead to the pattern revealed by these regression estimates.

The Patent Equation

Table V.3 displays the benchmark results for the patent and claims equations. The estimation results for the extended specifications are presented in Table V.4, but I do not report the coefficients for the six technology group variables, since they prove stable and highly significant across all specifications. This is not surprising, since patenting propensities have been shown to differ significantly across broad industry and technology groups (Bound, Cummins et al. 1984; Scherer 1983). The estimated coefficients of these dummy variables appear quite reasonable. As one would expect, the instruments sectors, electrical and electronics industries, machinery producing sectors and the chemical industries have high propensities to patent while food and metal using and producing sectors patent relatively less frequently. The coefficient on log R is also in the expected range reported by Bound et al. (1984). Finally, as in Scherer's (1983) study of patenting propensity, the logarithm of sales is positive and significant. The results for the CLAIMS regression are very similar to the estimates from the patent regression. Apparently, estimating the additional CLAIMS regression does not add a significant amount of additional information. This is also true for the specifications described below, so that I only present the estimates for the PATENT regressions.

Table V.4 displays the PATENT regression results with additional explanatory variables. All regressions results are corrected for heteroskedasticity, since the homoskedasticity assumption was rejected in a White test. The four measures of patent effectiveness ($PAPPR1^Y$ to $PAPPR4^Y$) from the Yale survey perform rather poorly. The χ^2-test statistic for the four patent effectiveness variables in specification (P2) is 7.35, which is not significant at the .1 level. The reason for this disappointing result is the inclusion of six relatively strong technology dummy variables, which capture already a considerable portion of the interindustry variance in patent effectiveness. The imitation lag variable IMLAG appears to have some additional explanatory power regarding patenting effectiveness. The supply sector variables in specification (P4) are separately and jointly significant at the .05 level. For the joint restriction on WSH10 and WHS10*C4 in specification (P4) , the χ^2-test statistic (2 degrees of freedom) is 10.19 and significant at the .01 level. A similar result applies to specification (P5) where the two variables SH45 and SH45*C4 are jointly significant at the .025 level (χ^2=8.879). Given the small size of the sample and the number of control variables included in the regressions, these results are surprisingly strong.

Table V.3
Benchmark OLS Regressions for Patents and Patent Claims

	Dependent Variable			
	log PATENTS		*log CLAIMS*	
CONSTANT	-8.354	(1.242)	-4.704	(1.061)
DCHEM	0.796	(0.232)	0.796	(0.260)
DFOOD	-0.718	(0.242)	-0.876	(0.271)
DMACH	0.890	(0.197)	0.991	(0.220)
DELEC	0.959	(0.235)	1.196	(0.263)
DINST	1.359	(0.370)	1.534	(0.415)
DMETAL	-0.273	(0.222)	-0.403	(0.249)
log R	0.549	(0.079)	0.563	(0.088)
log SALES	0.282	(0.102)	0.295	(0.114)
R^2	0.808		0.791	
N	118		118	
SEE	0.711		0.797	

These results confirm the expectation that patenting behavior may be affected in the presence of oligopolistic supply sectors. One can argue that better patent protection will strengthen the bargaining position of downstream firms visavi their suppliers. This argument assumes that oligopolistic suppliers can somehow affect the vertical rent distribution in their own favor. Hence, at the very least, the regression results support the notion of vertical competition. Downstream firms may attempt to strengthen their patent position by developing "patent thickets" for certain technologies, e.g. by applying for patents that protect minute details of the invention. It seems quite natural to assume that the marginal costs per patent are decreasing and that the payoff to such patenting strategies would rise with the extent of potential spillovers induced by firms in the supply sector. The positive coefficient for the supply sector variables (WSH10 and SH45) and the negative coefficient for the interaction terms (WSH10*C4 and SH45*C4) suggest that industries with a large number of firms react differently to concentrated upstream sectors than industries characterized by a small number of players. To my best knowledge, these estimates are the first that interpret patenting propensity as a function of vertical organization. Given the surprisingly strong results, it may be fruitful to extend this approach to other settings.[33] It should be noted that the statistical result from the regression analysis provides only indirect support for the threat of opportunistic behavior by suppliers, but I view these results as suggestive and encouraging for future work.

Table V.4
Dependent Variable: log PATENTS

	OLS-H (P1)	OLS-H (P2)	OLS-H (P3)	OLS-H (P4)	OLS-H (P5)
log R	0.499*** 0.065	0.515*** 0.061	0.480*** 0.073	0.493*** 0.075	0.492*** 0.073
log SALES	0.328*** 0.085	0.308*** 0.079	0.354*** 0.093	0.376*** 0.094	0.394*** 0.093
IMLAG	0.191** 0.075		0.188** 0.073	0.163** 0.076	0.164** 0.075
PAPPR1		0.142 0.119			
PAPPR2		-0.105 0.127			
PAPPR3		0.043 0.075			
PAPPR4		0.150 0.093			
SCIENCE1			0.179 0.141	0.217 0.141	0.236 0.144
SCIENCE2			-0.255** 0.096	-0.253** 0.096	-0.265*** 0.097
C4			-0.001 0.004	0.024** 0.010	0.008 0.005
WSH10				0.497** 0.211	
*WSH10*C4*				-0.010** 0.004	
SH45					2.393** 0.925
*SH45*C4*					-0.049*** 0.016
N	*118*	*118*	*118*	*118*	*118*
S.E.E.	0.692	0.693	0.682	0.672	0.674

*	significant at the .1 level (two-tailed test)
**	significant at the .05 level (two-tailed test)
***	significant at the .01 level (two-tailed test)

V.5 Discussion

The regression estimates described here seem to confirm the view that vertical organization matters for the determination of an industry's R&D

intensity. These results are consistent with von Hippel's (1982) suggestion that appropriability and structural conditions in vertically related industries may exert a strong influence on innovation incentives. Von Hippel's hypothesis links these conditions to the likelihood that the upstream or downstream sector becomes the source of innovation. This work has provided some evidence that the patterns of R&D spending may be affected as well. Both statements are ultimately consistent in that one expects (relatively) greater R&D expenditures to precede a consistently higher likelihood of achieving major innovations. A novel element of vertical interaction has also become apparent in the estimation of patenting behavior. The results suggest that information flows themselves may have great importance for the determination of R&D incentives. Such a conclusion comes as no surprise to institutionally oriented researchers or practitioners in research and development. However, the regressions support the view that information flows themselves are affected by different forms of vertical organization.

Despite the strong statistical evidence, the results should be interpreted with some care at this point, since they provide only circumstantial support for the theoretical models developed in previous chapters. Further support could be produced by demonstrating that changes in upstream organization can be related to subsequent changes in downstream R&D spending, entry, and production costs. Such tests will require longitudinal data of greater quality than were available for the regressions described in this chapter.

A promising alternative to purely cross-sectional data may be a panel of firm data in several (but few) closely related industries. For example, in the plastics materials industry, roughly fifteen broad materials groups (with some substitutability) can be identified. In the specialty segments, there appear to be only few producers, while the bulk material segments are densely populated by producers. The research and development activities of these producers are likely to affect the investment decisions of firms in the downstream plastics product industries, which again span some cross-sectional variance. However, since many of the underlying production technologies are similar (both in the plastics materials and the plastics products industry segments) one may be able to make a more conclusive argument than is possible with a large cross-section. Such an approach will require considerably greater data construction efforts than have been possible here, but - given the encouraging results described here - they may prove valuable to produce further insights into the relationship between vertical organization and research incentives.

FOOTNOTES FOR CHAPTER V

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[1] Another possibility would be to test whether particular forms of supply sector organization affect the structure of the downstream industry. Using entry and exit statistics for various industries, one could test whether the presence of "strong" suppliers is correlated with facilitated entry. Data of this type was not available for this study. Conceivably, there are other problems with such a test. Downstream industries may have means to deter entry, e.g. by limit-pricing strategies. In such a case the supplier would benefit already if it could create a permanent threat of entry by offering technical assistance to firms seeking to enter the downstream industry.

[2] A management problem of strategic R&D activities is that the research efforts themselves are often viewed by research engineers as a mundane form of sales service. See Graham and Pruitt (1990).

[3] By "strong" suppliers I mean upstream sellers of intermediate goods who can charge prices above marginal cost and who provide a large proportion of the industry's inputs.

[4] A more detailed discussion of these issues is given by Nelson and Winter (1977).

[5] Nelson and Winter provide several explanations for this counterintuitive result, but all of their arguments are based on the assumption that some variables are measured with error. The theoretical models developed above seem to imply another explanation: an industry's productivity and the R&D content of inputs may be determined endogenously. The coefficient on the variables measuring the R&D content of inputs will then be biased.

[6] Other aspects of this dataset are discussed in detail by Scherer (1984b) and in a comment by Mansfield. For example, it is well-known that patents can be of different value and importance. This view has been confirmed in recent research by Pakes (1986) and Trajtenberg (1990). In lines of business with few patents these heterogeneities could lead to biases.

[7] A detailed discussion of such efforts is given by Levin (1977) and Rosenberg (1976). The term "latent economies of scale" originates with Levin.

[8] A comparison between these results is made in Pavitt (1983).

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[9] These difficulties do not disappear if one tries to measure spillovers at the industry level. See Bresnahan's (1986) study of spillovers from mainframe producers to the financial services sector.

[10] Some theoretical work preceding Farber's study can be found in Binswanger and Ruttan (1978) who discuss a supplier's incentives to create a bias in the direction of technological change.

[11] See for example Cohen and Levin (1989) for a summary of cross-sectional studies and and comments on their potential shortfalls.

[12] The formal argument is stated in the appendix to chapter III. Once sunk costs other than those of R&D determine industry structure, the effect of upstream spillover production on downstream industry structure will be comparatively small.

[13] Although I refer to the second effect as the "cost reduction effect", the logic can equally be applied to product innovations that enhance the demand for the supply sector's commodity.

[14] The distinction is discussed in chapter IV. By output restriction I mean the difference in downstream industry output between i) a perfectly competitive industry in which all firms produce with the low-cost technology and ii) an oligopolistic or monopolistic downstream industry where firms produce less than the competitive output in order to extract rents.

[15] This hypothesis originated with Galbraith (1952). Theoretical and empirical studies relating to it are discussed in detail in Scherer (1980).

[16] This is the classical vertical restraint problem. Under ideal circumstances, the upstream producer will appropriate the full downstream surplus and <u>not</u> affect downstream incentives for cost reduction in a negative way.

[17] For example, the Dasgupta-Stiglitz model predicts that R&D expenditures will decrease with higher cost parameters β. See chapter III, equation (10). The Dorfman-Steiner model makes a similar prediction. However, high input costs may induce R&D with the purpose of substitution in which case this relationship may no longer hold.

[18] For example, in the Dasgupta-Stiglitz model or in Tandon's (1984) model of R&D, factor prices do not affect the industry's R&D intensity. Note that this statement will not hold if innovation is factor-biased or if the cost curve is not isoelastic in R&D. However, the effect on R&D intensity will

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still be of second order. Note also that if the inputs for research and development activities became available at a lower price, R&D expenditures would rise, and so would R&D intensity.

[19] Mishina (1989) has pointed out that spillovers may occur in equilibrium if joint development of a new technology with a supplier's help conveys some benefit on the cooperating downstream firm. In Mishina's model, joint development has a strong positive effect on the profitability of the downstream industry. In this case, a downstream firm will engage in R&D although spillovers will occur with certainty. See chapter II for a more detailed discussion of Mishina's model.

[20] Using a dependent variable that reflects sunk cost investments (see Levin and Reiss (1988) and the appendix to chapter III) yielded very similar results.

[21] Again this raises the thorny issue of additional endogenous relationships. If government-funded R&D has side effects (e.g. "spillover effects" from the government funded to the privately funded projects) then private R&D incentives are affected by the extent of contract R&D and vice versa. Levin and Reiss (1984) model government-funded R&D in a simultaneous equations model together with company-financed R&D and advertising. The inclusion of the contract R&D equation does not appear to have a great empirical payoff. See also Lichtenberg (1987, 1988) for studies concerning the effect of government-sponsored R&D on private incentives.

[22] Some of these measures have also been used by Levin, Cohen and Mowery (1985).

[23] The significance level associated with asymptotic t-statistics has to be corrected under these circumstances , e.g. by following the Bonferroni approach. I omit this correction, since I am using these variables primarily as industry-specific controls.

[24] For details of variable definition see Table IV.A.1 in the appendix.

[25] The Levin et al. survey also measures the contributions of materials suppliers (MATSUP). None of the regression results include this variable, since it had a very small and insignificant coefficient in all specifications. The results did not indicate any tradeoff between the MATSUP and vertical organization variables.

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[26] The underlying assumption is here that upstream contributions can be additive.

[27] These calculations are based on Miller and Blair (1985, ch. 5). Only the supply of intermediate inputs is captured in the supply sector measures. Capital goods were excluded for two reasons. First, investments in capital goods tend to be "lumpy", i.e. only weakly coupled to output. Second, it is virtually impossible to obtain reasonably precise measures of capital goods flows from standard IO tables. The BEA data from which such variables could be constructed were not available for this analysis. For details on the use of the BEA capital goods flow data, see Scherer (1984b, p. 430).

[28] Initially, I classified upstream industries according to their four-firm concentration ratio into intervals from 0 to 15, 15 to 30, 30 to 45, and 45 to 60, and greater than 60 per cent. Since the inclusion of five variables (plus five interaction effects) would reduce the degrees of freedom considerably, I aggregate the first three groups (supply industries with a four-firm concentration ratio of less than 45 per cent) and the last two (supply industries with a four-firm concentration ratio equal to or greater than 45 per cent (SH45)). This cut-off point was chosen in order to minimize the effect of errors in variables, since the variable values in the fifth category were small in most industries. However, the regression results do not change qualitatively if, instead of SH45, the cost share of intermediate goods supplied by industries with concentration greater than sixty per cent is used.

[29] These data were compiled by Judy Chevalier (M.I.T.) from Scherer's master tape documenting his analysis of more than 15.000 patents granted to firms in the FTC sample during the period from June 1976 to March 1977. See Scherer (1984b).

[30] See Bound et al. (1984) for a discussion and comparison of various estimation approaches. See also Hausman, Hall, and Griliches (1984) for a discussion of estimation models for panel data.

[31] See Griliches's discussion of the relatively large intra-industry variance in his comment to Levin et al. (1987).

[32] Including one of the supply sector variables (WSH10 or SH45) and one of the technology flow variables (EXTERN1 or EXTERN2) without the

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respective interaction terms produces only small and insignificant coefficients. These results are not shown in the two tables V.1 and V.2.

[33] Scherer (1983, p. 109) notes that in automobile assembly, the number of patents per million dollars of R&D outlays was only 0.28, while the respective figure for producers of automobile parts was 4.35. Scherer points out that the automobile parts industry may be more concerned with developing new technology than car assemblers are, but the statistical picture is also consistent with excessive patenting in the face of information spillovers promoted by monopsonistic buyers. Domestic car assemblers in the United States have had an explicit policy to disseminate innovations originating with any supplier across their whole supply base (Helper 1990).

Appendix to Chapter V

Table A.V.1

This table describes the variable definitions. Data sources are given in parentheses.

RS	R&D Intensity (defined as company-financed R&D expenditures in 1976 divided by total line of business sales and transfers (FTC))
APPR	Appropriability measure (Yale Survey, maximum score of responses to questions IA1..IA6 and IB1..IB6)
IMLAG	Imitation lag time for a major patented product innovation (Yale Survey, question IIF1)
INCELAS	Income Elasticity (Levin 1981).
PELAS	Price elasticity of demand (Levin 1981)
GROWTH	Time shift parameter (Levin 1981)
EQSUP	Contribution to technical change by suppliers of research and production equipment (Yale Survey, average score of responses to question IIIE3 and IIIE4)
USERS	Contribution to technical change by users of industry output (Yale Survey, question IIIE5)
GOVUNIV	Contribution to technical change by government agencies/laboratories and university research (Yale Survey, average score of responses to questions IIIE6, IIIE7 and IIIE8)
SCIENCE1	Relevance of scientific and engineering disciplines to technical change (Yale survey, average score of responses to question IIIAI, items a, b, d, e and question IIIA2, items c, d, e)
SCIENCE2	Relevance of of scientific and engineering disciplines to technical change (Yale survey, average score of responses to question IIIAI, item c and question IIIA2, items a, b, and f)
NEWPL10	Percentage of property, plant, and equipment installed within five years preceding 1976 (FTC) (divided by a factor of 10)
C4	Four-firm concentration ratio (COM 1977).

WSH10	Aggregate weighted factor cost share, sum of factor cost shares of intermediate inputs weighted by the respective supply sector's four-firm concentration ratio (IO 1977, COM 1977) (divided by a factor of 10)
SH45	Factor cost share of intermediate inputs supplied by supply sectors with C4≥45(IO 1977, COM 1977)
EXTERN1	Value of R&D (private goods assumption) flowing in from other sectors divided by sales of the receiving industry (Scherer 1984)
EXTERN2	Value of R&D (public goods assumption) flowing in from other sector divided by sales of the receiving industry (Scherer 1984)
PATENTS	Number of patents granted to firms in the FTC sample (Scherer 1983)
PAPPR1	Strength of patent protection (Yale survey, response to question IAI)
PAPPR2	Strength of patent protection (Yale survey, response to question IA2)
PAPPR3	Strength of patent protection (Yale survey, response to question IB1)
PAPPR4	Strength of patent protection (Yale survey, response to question IB2)
CLAIMS	Number of patent claims contained in patents granted to firms in the FTC sample (Scherer 1983)
DCHEM	Dummy variable for chemical industries
DELEC	Dummy variable for electrotechnical and electronics industries
DMACH	Dummy variable for machinery producing industries
DINST	Dummy variable for instruments producing industries
DMETAL	Dummy variable for primary and secondary metals industries
DFOOD	Dummy variable for food industries

Data Sources

FTC	Federal Trade Commission. *Annual Line of Business Report.*
COM 1972	U.S. Bureau of the Census. *1972 Census of Manufactures.*
COM 1977	U.S. Bureau of the Census. *1977 Census of Manufactures.*
Yale Survey	Levin et al. (1987)

All patent data and technology flow variables utilize Scherer's (1983) dataset.

Table A.V.2

Sample Statistics

Variable	Mean	Std. Dev.	Minimum	Maximum
RS	1.7765	1.7366	0.0895	8.5105
PELAS	1.8248	1.6969	1.0000	9.2100
INCELAS	0.9003	0.5387	0.0000	2.0000
GROWTH	0.9395	0.9810	-1.7899	2.9971
APPR	6.0143	0.5674	4.0000	7.0000
IMLAG	3.7945	0.9335	1.0000	6.0000
SCIENCE1	3.9950	0.5638	2.2857	5.2857
SCIENCE2	3.0946	0.7251	1.5000	6.0000
GOVUNIV	2.7483	0.9197	1.0000	5.7500
EQSUP	4.2726	0.8394	2.0000	6.0000
USERS	4.0279	1.0280	1.0000	7.0000
NEWPL10	3.8700	0.9347	1.5000	6.5000
SH45	0.1799	0.1390	0.0036	0.6419
WSH10	2.3581	0.6973	0.6288	4.5392
C4	42.5580	19.6620	7.0000	93.0000
EXTERN1	0.6762	0.7857	0.0132	6.9572
EXTERN2	3.7845	2.9387	0.4155	18.2230
NOPATS	97.8670	184.0100	1.0000	1228.0000
NOCLAIMS	720.2500	1505.8000	3.0000	11082.0000
log PATENTS	3.4372	1.5531	0.0000	7.1131
log CLAIMS	5.2965	1.6701	1.0986	9.3131
DMETAL	0.1333	0.3414	0.0000	1.0000
DCHEM	0.1417	0.3502	0.0000	1.0000
DFOOD	0.1417	0.3502	0.0000	1.0000
DMACH	0.2333	0.4247	0.0000	1.0000
DINST	0.0417	0.2007	0.0000	1.0000
DELEC	0.1250	0.3321	0.0000	1.0000
log R	9.6192	1.6303	5.9162	14.2320
log SALES	14.1940	1.2554	11.7860	18.0600
PAPPR1	3.4068	0.9408	1.5000	6.0000
PAPPR2	3.2639	1.1498	1.0000	7.0000
PAPPR3	4.1840	1.0817	2.0000	7.0000
PAPPR4	3.7425	1.1880	1.0000	7.0000

Note: 120 observations for each variable with the exception of *log R* for which only 118 observations were available.

Chapter VI

Discussion and Conclusions

The theoretical and empirical results that I have presented in the body of the thesis have explored some aspects of the relationship between vertical organization and R&D incentives. In section VI.1, I will summarize these results briefly and then, in section VI.2, discuss the implications of this work for the theoretical understanding of R&D incentives and for managerial practice. Section VI.3 presents some suggestions for future research and concludes.

VI.1 Summary of Theoretical and Empirical Results

In chapter I of the thesis I introduced the basic premise of this work: our understanding of R&D incentives will be incomplete and probably biased if the linkages between vertically related sectors are not explicitly taken into account in theoretical and empirical work. Specifically, I suggested that such interindustry linkages may give rise to strategic R&D incentives that cannot be detected in one-sector models. I then introduced the notion of a strategic appropriation mechanism which involves i) providing to firms in a vertically related sector technological knowledge as a public good and ii) capturing a return from an externality effect caused by the dissemination of this knowledge. Strategic appropriation involves then the intentional production of "spillover knowledge." I hypothesized that firms with large market shares would be in a particularly advantageous position to employ the strategic appropriation mechanism because of their ability to capture benefits from interindustry externalities.

In chapter II, I began by reviewing the literature on R&D spillovers which is, to a large extent, based on the assumption that spillovers are an uncontrollable, exogenously given phenomenon. Only few attempts have been made recently to treat information spillovers as an endogenously determined information flow, e.g. by Mishina (1989). The concept of intentional spillover production is - to my best knowledge - completely novel to the economics literature. However, case studies from the industrial purchasing, management of technology, and industrial marketing literatures support the view that firms frequently produce technological knowledge and make it available freely to firms in vertically related industries. I cited evidence describing this practice between materials producers and their buyers, between producers of computer hardware and software, and between electric and gas utilities and their industrial customers. This evidence constituted the basis for the models developed in chapters III and IV.

In the model presented in chapter III, I showed that a monopolist supplier may have incentives to spill over knowledge to downstream firms in order to increase the degree of downstream competition, even at the cost of reduced downstream R&D incentives. Producing public goods information lowered the downstream firms' R&D investments necessary to enter the industry so that a larger number of firms became sustainable in the spillover equilibrium than in the "stand-alone" industry.

In chapter IV, I first derived conditions under which upstream firms would have incentives to introduce innovations before any of their downstream customers could profitably do so. I then analyzed the incentives of a monopolist supplier to preempt downstream innovators in cases where innovation would lead to increased downstream market power.

I demonstrated in these models that suppliers holding large market shares and enjoying high returns on their sales may be sufficiently interested in the extent of innovation and competition in other industries to employ the strategic appropriation mechanism. Even if integration into downstream production is infeasible or undesirable, the production of public goods knowledge for the downstream sector may be profitable. The results of the models also suggested that the strategic incentives of these suppliers would be weakened by greater concentration in the buyer industry.

In chapter V, I tested the theoretical results in a cross-section of industries. I hypothesized that fragmented downstream industries will be characterized by a lessened R&D intensity if their upstream supply sectors accounted for large shares of downstream production costs and if these supply sectors were strongly concentrated. The dataset was constructed by combining cross-sectional R&D data from the Federal Trade Commission Lines of Business database with measures of supply sector organization derived from input-output tables. The estimation results provided strong support for this hypothesis.

I also found that the effect of interindustry technology flows on an industry's R&D intensity varied with the structure of the recipient industry. In industries with very low concentration ratios, technology flows from external sources caused a strong substitution effect, while the R&D intensity of highly concentrated sectors was increased by greater technology flows. This differential impact of the technology flow variables suggests that fragmented and more concentrated industries either receive very different forms of embodied knowledge from their supply sectors, or that they react differently to these technology flows. Finally, I undertook an analysis of patenting behavior, based on the tentative hypothesis that vertical competition for rents should lead customers of "strong" suppliers to seek stronger patent protection. This hypothesis was confirmed when tested with aggregate measures of industry patents.

Taken together, these results appear to me to be interesting in several ways. First, they demonstrate that vertical organization is a strong determinant of R&D incentives and patenting propensity. Second, they provide support for the strategic appropriation hypothesis. Some care needs to be applied, however, in assigning causal relationships. Some of my results are consistent with a market failure hypothesis: downstream R&D incentives may be lessened in the presence of upstream market power, but there may be no increased upstream R&D efforts to compensate for diminished downstream incentives.[1] More empirical work is needed to explore this alternative hypothesis in greater detail, but the existing results support the view that vertical shifts of R&D incentives are indeed occurring in a chain of production activities.

VI.2 Implications for Theory and Managerial Practice

Intentional Spillover Production as a Novel Concept

The concept of intentional spillover production is - to the best of my knowledge - novel to the economics literature. In the two modelling chapters included in this thesis I have shown that firms may have incentives to contribute to technical change in sectors other than their own even if they cannot trade the respective R&D knowledge or embody it in tradeable products. The mechanism that makes research and development contributions profitable despite this market failure is based on the existence of interindustry externalities. Particularly in settings where the structural conditions allow firms to capture externality benefits, e.g. from enhanced demand or lower input prices, we have to allow for the possibility that the R&D efforts of firms in one industry are targeted at improving the productivity and product quality of firms in other sectors without receiving a direct compensation for these efforts.

Often it will be possible to trade technological information with imperfect efficiency, as the results by Caves, Crookell, and Killing (1983) suggest. Note that the existence of imperfect markets for intellectual property will strengthen the supplier incentives discussed in this work, but as I showed in chapters III and IV, even the complete failures of these markets will not preclude suppliers to become a contributor to downstream innovation. The models should also not be understood as a statement that all spillovers are necessarily endogenous or even intentional. However, to claim that spillovers always represent leakage phenomena appears equally simplistic. In order to get closer to a more realistic description of information and knowledge one has to differentiate the intentional and unintentional production of spillovers. This distinction has been neglected so far in the R&D literature.

Implications for the Economics of R&D Consortia

A particularly interesting characteristic of interindustry spillovers is their effect on the vertical rent distribution. This effect raises the question whether horizontal cooperation in R&D can have a role in restructuring the profitability conditions within a chain of production activities. This aspect of

R&D consortia has to my best knowledge not yet been explored in the literature. Producers in one industry could conceivably pool their R&D resources to affect a supplier or buyer sector by providing technical or other information. Such a move could "level the playing field" in the related sector and remove asymmetric distributions of technological capabilities as well as vertical distortions that were present in the ex ante state. This effect is very similar to the one described by Mishina (1989) in the case of endogenous, yet unintentional intra-industry spillovers via supplier firms.

Implications for the Sources of Innovation

While I have focused in my theoretical and empirical analysis on R&D incentives, there is a strong link between this work and research on the sources of innovation. VanderWerf (1990a) and von Hippel (1988a) have pointed out that suppliers of commodity materials are in some industries the dominant contributors to technical change. The work presented here has provided a formal theoretical foundation for their results, since one would expect a consistent pattern of successful innovation to be correlated with an analogous pattern in R&D spending. But in addition, I have been able to show that this phenomenon is not limited to a small number of cases. The cross-sectional estimation results suggest instead that vertical shifts in R&D spending are an economy-wide phenomenon.

Implications for the Measurement of R&D Elasticities[2]

Overlooking the role of intentionally produced spillovers may lead to misleading results from theoretical models. Moreover, as I pointed out in chapter III, R&D elasticity estimates may be biased if such models are used as the basis for empirical analyses. Low industry R&D expenditures can be consistent with high R&D elasticities if suppliers or firms in other vertically related sectors provide technological information that can be used as a substitute for own R&D efforts. Interindustry flows of information and technology must be incorporated in empirical studies in order to produce unbiased estimates of R&D elasticities. This is a complex econometric problem, since an industry's own R&D efforts and these flows will in all likelihood be determined simultaneously.

Implications for Technology Strategy Formulation

A growing literature[3] on technology strategy is trying to provide a link between the theoretical results produced by theoretical and empirical researchers and the managerial decision problems of developing long-term R&D objectives and strategies, and implementing them within organizations. But as Adler (1989, p. 29) has pointed out in a recent survey of this literature, relatively few studies have "explored the ability of the firm to actively reshape its environment." The results produced in this thesis can contribute to the technology strategy literature by emphasizing the inherently strategic role of certain R&D investments. R&D may not only have an important role in improving the firm's productivity and the appeal of its products, but it may be a strategic instrument to control and shape the competitive conditions in vertically related sectors. The evidence from case studies suggests that this form of research and development effort can be extremely profitable for an enterprise.[4] The thesis has provided some theoretical approaches that may prove helpful in evaluating the conditions under which an enterprise should seek to affect technological progress in other sectors.

Many questions remain with respect to the management of strategic R&D efforts. The R&D boundary of a firm using strategic appropriation mechanisms differs substantially from its manufacturing boundary. What are the consequences of such a separation of boundaries for organizational behavior? Under what circumstances should the firm integrate forward into downstream production and realign the organizational boundaries? Can the "crowding-out" effect discussed in chapter III have negative long-term consequences for the strategically acting firm? To anwer these questions we will have to build a more comprehensive body of knowledge regarding strategic R&D and its management than is available at this point.

VI.3 Future Research and Conclusions

Section VI.2 contained already several suggestions for future research, but before I conclude with this section I want to emphasize three topics that appear especially relevant and promising to me.

The first suggestion concerns a possible link between my empirical results and the literature on "technological regimes".[5] A particularly striking pattern in my empirical results is the strong moderating effect that industry concentration has on an industry's R&D response to technological flows into the industry. A possible explanation is that these differences are caused by the existence of behaviorally different "R&D regimes." Regime-dependent R&D behavior has been documented by a growing number of researchers, e.g. Winter (1984), Acs and Audretsch (1988), and Audretsch (1990). The results reported here suggest that regime-dependence with respect to vertical interactions may play an important role in determining patterns of R&D activity. The nature of the innovation process may vary substantially with different forms of supply sector organization. Exploring and specifying different R&D regimes and estimating a multi-regime model may be a fruitful avenue for future work.

Another natural extension of the theoretical work reported here is to model the quality of intermediate inputs in more detail. Such a model may again help to explain the coefficient signs of the technology flow variables in the regression results of chapter V. Some results on this topic have been produced by Porter and Spence (1977), but the issue is still vastly underresearched. Again, such an analysis will require a multi-sector model of R&D incentives in which exogenously or endogenously determined industry structure is likely to play an important role. A particularly important question is the effect of inputs on downstream technological progress. Economists have long argued that technology flows can be either substitutes or complements in downstream knowledge production (Nelson and Winter 1977). However, as with information flows, these qualities have been assigned as exogenous characteristics. A consequent extension of the model developed in chapter III would give upstream suppliers a choice between the production of complements to or substitutes for downstream knowledge, and let them choose the most profitable option.

Much of the material presented here focuses on well-defined factor markets in which firms have arms-length relationships. This field of study becomes more complex, but also much richer if small numbers situations and more complex contractual instruments are taken into account. In my own research I have started to explore some of these issues in case study work not included in this thesis (Harhoff 1991). Such in-depth studies are likely to reveal interesting behavioral constraints that firms are facing in managing vertical relationships and R&D. Much work remains to be done to produce a body of knowledge that can explain and even guide strategic choices in the management of vertical relationships.

This list of implications and suggestions is not exhaustive, but the discussion in this chapter has demonstrated the need for further research into the relationship between R&D incentives and vertical organization. This topic has been much neglected in past investigations, but more research efforts in this area should contribute valuable new insights to out understanding of the innovation process. Innovations do not just emerge in one industry. Their creation draws on a complex system of institutions and resources, including vertically related sectors that contribute information and physical inputs. This thesis has provided a set of results that may serve as a basis for refined measurement efforts, but also as the starting point of further theoretical work into the nature of this system. The results reported here should prove encouraging for those who to solve the "differential innovation puzzle" (Nelson and Winter 1977) with answers that go beyond simple industry and technology classifications.

FOOTNOTES FOR CHAPTER VI

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[1] The explanation is based on the assumption that upstream firms do not realize that their downstream buyers make insufficient R&D investments, or that they cannot react to the innovation failure with compensatory measures. Both assumptions appear overly stark.

[2] This term refers to the elasticity of cost and product quality with respect to R&D expenditures.

[3] For a survey, see Adler (1989). Roberts (1988) presents an extensive survey of the literature concerned with the management of technology.

[4] For example, Graham and Pruitt (1990, p. 372) note that Alcoa's R&D investment in can sheet and can technology development paid off with a "return on research" of better than 100 to 1. How strategic appropriation will affect business performance on average is of course an open question. An evaluation of the effectiveness of this strategy and of its effect on business performance (Venkatraman and Ramanujam 1986) would be possible if data on strategic investments were available at the firm level.

[5] See Winter (1984) for a detailed discussion of the concept of technological regimes.

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