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INFORMATION SHARING AND THE STABILITY OF COOPERATION IN RESEARCH JOINT VENTURES*

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RÉSUMÉ

Cet article examine le partage de technologie et la stabilité de la coopération dans les consortiums de recherche (RJV) dont le but est la réduction des coûts de production. Dans un jeu à quatre étapes, les firmes prennent des décisions quant à leur participation à la RJV, au partage d'information, à leurs dépenses en R&D et à leur output. Une caractéristique importante du modèle est que le partage volontaire d'information au sein de la RJV augmente les fuites d'information vers les non-membres. On montre que c'est l'externalité de la RJV vers les non-membres qui détermine la décision des membres de partager (ou non) l'information, alors que c'est l'externalité affectant toutes les firmes qui détermine le niveau de partage d'information au sein de la RJV. Les RJV représentant une plus grande proportion des firmes dans l'industrie ont davantage tendance à partager l'information. Lorsqu'il n'en coûte rien de partager l'information, les firmes ne choisissent jamais des niveaux intermédiaires de partage d'information : l'information est partagée au complet ou pas du tout. La taille de la RJV dépend de trois effets : un effet de coordination, un effet d'information et un effet de concurrence. Dépendamment de l'importance relative de ces trois effets, la taille de la RJV peut augmenter ou diminuer avec les externalités. L'effet du partage d'information sur la profitabilité des firmes ainsi que sur le bien-être est examiné.

Mots clés : externalités de recherche endogènes, partage d'information, coopération en R&D, consortiums de recherche

ABSTRACT

The model studies information sharing and the stability of cooperation in cost reducing Research Joint Ventures (RJVs). In a four-stage game-theoretic framework, firms decide on participation in a RJV, information sharing, R&D expenditures, and output. An important feature of the model is that voluntary information sharing between cooperating firms increases information leakage from the RJV to outsiders. It is found that it is the spillover from the RJV to outsiders which determines the decision of insiders whether to share information, while it is the spillover affecting all firms which determines the level of information sharing within the RJV. RJVs representing a larger portion of firms in the industry are more likely to share information. It is also found that when sharing information is costless, firms never choose intermediate levels of information sharing : they share all the information or none at all. The size of the RJV is found to depend on three effects : a coordination effect, an information sharing effect, and a competition effect. Depending on the relative magnitudes of these effects, the size of the RJV may increase or decrease with spillovers. The effect of information sharing on the profitability of firms as well as on welfare is studied.

Key words : endogenous R&D spillovers, information sharing, R&D cooperation, research joint ventures

1. Introduction

R&D cooperation incorporates three dimensions: the coordination of R&D expenditures, information sharing, and the stability of the cooperative venture. The coordination of R&D expenditures induces firms to internalize innovation externalities; information sharing increases R&D spillovers between cooperating firms; and the instability of cooperation arises because cartels are vulnerable to individual and coalitional deviations.

A large theoretical literature on R&D cooperation and competition now exists, starting with the seminal paper of d'Aspremont and Jacquemin (1988). Most of this literature has focussed on the coordination of R&D spending, with little attention being devoted to the information sharing dimension or to the stability of cooperation. Generally, information sharing and Research Joint Venture (RJV) formation have been analysed separately. Typically, the extent of information sharing has been assumed exogenously, and cooperation has been assumed to be industry-wide (the industry itself being often composed of a duopoly). However, important interactions between information sharing and RJV formation arise. The level of information sharing affects the attractiveness of the cooperative venture to outsiders, and also affects the willingness of cooperating firms to admit additional members. A thorough understanding of R&D cooperation requires the study of the interactions between information sharing and RJV formation. This paper attempts to remedy this gap by studying the endogenous determination of information sharing, together with endogenous RJV formation.

Two approaches coexist in the literature regarding information sharing. The first assumes that information sharing is not affected by cooperation, in which case cooperating firms simply coordinate R&D expenditures. The second assumes that cooperating firms share all of their research results. Both assumptions are arbitrary, and lack theoretical as well as empirical foundations. While it is reasonable to assume that information sharing is improved by cooperation, there is no foundation for the assumption of perfect information sharing.

Consider next the question of industry-wide cooperation. Studies have typically assumed that all industry members participate in the RJV. When the size of the RJV is endogenized, information sharing is generally exogenous. Only De Bondt and Wu (1997) and Katz (1986) have addressed jointly RJV stability and information sharing. De Bondt and Wu (1997) study an R&D cooperation model with insiders/outsiders. The effect of different levels of information sharing is addressed, although information sharing remains exogenous. They find that an industry-wide RJV quickly becomes stable for relatively low levels of information sharing. Katz (1986) is the only paper that simultaneously endogenizes information sharing and RJV formation. In his model, firms decide on their RJV membership, R&D cost sharing and information sharing rules, R&D expenditures, and output. The model shows that cooperation is beneficial when product market competition is low, when spillovers are important, and when cooperation improves information sharing. With industry-wide cooperation, full information sharing is adopted. The conditions for the emergence of industry-wide cooperation are characterized. However, the model focuses on polar cases: no exogenous spillovers, and either industry-wide or no cooperation.

In the model studied here both information sharing and participation in the RJV are endogenous. In a four-stage game-theoretic model, firms decide on participation in a RJV, information sharing, R&D expenditures, and output. There are two types of exogenous spillovers: those affecting all firms, and those from the RJV to outsiders. Moreover, RJV members may decide to share information among themselves. An important feature of the model is that voluntary information sharing between cooperating firms increases information leakage from the RJV to outsiders. The underlying argument is that sharing information increases the likelihood that this information leaks out to third parties.

Spillovers can be endogenous in two (non-exclusive) ways. First, by investing in learning and improving their absorptive capabilities, firms can increase the effective information they receive from other agents (Cohen and Levinthal, 1989; Adams, 2000). Second, by controlling how much information leaks out, firms can impact the level of outgoing spillovers. Ultimately, therefore, a flow of information is affected by the behaviour of both the source and the destination of the information. This paper focusses on the control of firms over outgoing spillovers through their information sharing decisions.

It is found that it is the spillover from the RJV to outsiders that determines the decision of insiders whether to share information or not, while it is the spillover affecting all firms that determines the level of information sharing within the RJV. Larger RJVs are more likely to share information. This result shows the importance of the interaction between RJV size and information sharing. It is also found that when sharing information is costless firms never choose intermediate levels of information sharing: they share all the information or none at all. The model predicts that the absence of information sharing is due to competitive impediments (leakage of information to non-RJV members), while intermediate levels of information sharing would arise as a result of other considerations: costs of sharing information, or limited compatibility of firms' technologies. The size of the RJV is found to depend on three effects: a coordination effect, an information sharing effect, and a competition effect. Depending on the relative magnitudes of these effects, the size of the RJV may increase or decrease with spillovers. Paradoxically, the size of the RJV may increase with the leakage from the RJV to outsiders. The effect of information sharing on the profitability of firms as well as on welfare is studied.

Some studies have addressed information sharing and the size of the RJV, albeit separately. These studies are briefly discussed here, along with some empirical evidence showing that the assumptions of exogenous information sharing and of industry-wide cooperation are unsatisfactory.

A number of studies have addressed the issue of technology sharing between competitors, without taking into consideration the interactions between information sharing and the stability of cooperation, however. Kamien et al. (1992) study both the case where cooperation entails no information sharing and the case where it entails maximum information sharing. d'Aspremont et al. (1996) consider the problem of bargaining over the disclosure of interim research knowledge in a R&D race for a patentable innovation between two firms. Katsoulacos and Ulph (1998a, 1998b) endogenize R&D spillovers taking into account distinctions such as whether firms are in the same industry or not, product versus process innovations, technical substitutability or complementarity, and information sharing versus research coordination. Poyago-Theotoky (1999) allows duopolistic firms to choose the spillover level after R&D investments are undertaken; she finds that cooperating (non-cooperating) firms choose maximal (minimal) spillovers. Kamien and Zang (1998) allow firms to choose an "R&D approach" which determines how much the firm can benefit from other firms' R&D. Combs (1993) develops a model where R&D cooperation increases the probability of innovation by sharing information about research strategies and outcomes. De Fraja (1990, 1993) investigates whether firms have an incentive to disclose their research results or not. Rosenkranz (1998) studies firms' incentives to form RJVs in an incomplete information framework when technological know-how is private information; two firms first decide on cooperation and information revelation and then compete for a patent. Finally, Bhattacharya et al. (1990)

develop a two-stage model where researchers may share endowments of productive knowledge in the first stage and choose R&D efforts independently in the second stage.

Some studies have focussed on the moral hazard dimension of technology sharing. Pérez-Castrillo and Sandonís (1997) study a model in which the disclosure of information makes the expected cost of the project lower. An RJV may fail to form because of the moral hazard problem arising from the difficulty of contracting upon the transfer of information. They find that penalties can alleviate the incentive problem and the individual rationality constraints. Bhattacharya et al. (1992) consider a three-stage model of R&D where firms can share knowledge prior to choosing unobservable R&D levels and competing in the product market. d'Aspremont et al. (1998) consider RJVs with adverse selection in knowledge sharing and moral hazard in private development efforts.

Empirically, R&D cooperation with and without information sharing is observed.[2] Branstetter and Sakakibara (1997) find evidence of increased knowledge spillovers within Japanese research consortia. They report that access to complementary knowledge of other RJV members is the most highly cited motive behind participation in research consortia by R&D managers. Mariti and Smiley (1983) studied 70 cooperative agreements between European firms that took place in 1980, and found that one way flows of information were behind 41% of agreements, while information sharing (two-ways flows of information) were behind 29% of agreements. Cassiman and Veugelers (1998), from the study of a sample of firms from the Belgian manufacturing industry, find that spillovers received by a firm tend to be higher when the firm engages in cooperative R&D, which is consistent with improved information sharing between cooperating firms. Adams (2000), from the study of a sample of R&D laboratories in the chemicals, machinery, electrical equipment, and transportation equipment industries, finds that learning expenditures increase in response to spillovers, which is an indication that spillovers are endogenous.

However, willingness to share some information does not mean that firms necessarily share all of their research results. Imperfect information sharing may arise because of technical difficulties, differences in organizational culture, and strategic factors (De Bondt and Wu, 1997). The distinctive nature of the technologies of some firms may impose constraints on the extent of cooperation and information sharing with other firms (Uenhora, 1985). Firms also have discretion over how much information they effectively disclose. A firm can affect the spillover rate through the choice of the location of its laboratories, or by controlling the participation of its researchers in scientific conferences (De Fraja, 1990). Bhattacharya et al. (1992) report reluctancy on the part of some firms to send their best researchers to the RJV.

The regulation of information sharing can be found in the cooperative agreement itself. The US Department of Commerce estimates that one year is the minimum length of time required to reach agreement on the research agenda between cooperating firms (Link and Tancy, 1989). This shows the complexity of the negotiation mechanism behind research output sharing contracts. The European cooperative research programs Esprit and Race require cooperation and information sharing, while the program Eureka requires cooperation but not information sharing (Fölster, 1993).

[2] See Cassier and Foray (1999) for a discussion of the rules governing the sharing of research results in eight biotechnology research consortia.

Fransman (1990) addresses the issue of information sharing in terms of research facilities. He distinguishes between cooperative research where firms keep distinct research facilities -in which case the level of information sharing is low- and cooperative research where firms use joint research facilities -in which case we can expect higher levels of information sharing. Firms may want to maintain both types of cooperative agreements in parallel. In some cases, they may wish to share information more thoroughly with suppliers/distributors, and less with competitors. In Japan, separate research facilities between cooperating firms seem the norm, not the exception. There is evidence that the propensity to share knowledge is lower for commercializable devices, and when inter-firm competition is important (Fransman, 1990).

Consider now the second dimension, the stability of cooperation. De Bondt et al. (1992) study the stability of a RJV assuming that information sharing is not improved by cooperation, and that spillovers between the RJV and outsiders are symmetric. Poyago-Theotoky (1995) analyzes a model with spillovers where one RJV forms endogenously, assuming that cooperation entails maximal information sharing. Kamien and Zang (1993) study an industry where several competing RJVs form endogenously. Yi and Shin (2000) examine the endogenous formation of RJVs when many RJVs can form, and study the effects of exclusive membership versus open membership rules. Yi (1998) studies the stability of cost reducing joint ventures with exogenous cost reduction. Greenlee (1998) studies the stability of RJVs that share information but do not coordinate R&D expenditures; while information sharing in RJVs is imperfect, it remains exogenous. Kesteloot and Veuglelers (1995) study the stability of R&D cooperation in a two-firms repeated game model. Eaton and Eswaran (1997) study the formation of technology-trading coalitions with an infinite horizon. However, in all of these studies, while the size of the cooperative venture(s) is endogenous, information sharing is exogenous.

The assumption of industry-wide cooperation (common in the literature) is at odds with empirical evidence. Most RJVs comprise only a subset of firms of a given industry. From the examination of 27 cooperative research agreements, Combs (1986) finds that in no case did the agreement include an entire industry. Industry-wide RJVs are generally directed at industry regulatory problems (Peck, 1986). Snyder and Vonortas (2000) find that many RJVs are constituted of a large number of firms; The MCC (Microelectronics and Computer Technology Corporation) research consortium included 21 participating firms. This makes the standard duopoly framework even less appropriate for the study of RJVs.

There are many reasons why one or more firms may decide not to participate in a RJV. Firms in an industry may take different technological paths, and may hence have more technological affinities with some firms than with others. Moreover, asymmetries between firms may lead some firms to opt out of the RJV. It may also be the case that the RJV is composed of more advanced firms in the industry, and that less advanced firms are not allowed in. In the same token, the RJV may be formed by technologically backward firms that are trying to catch up with the leaders, in which case the latter have no interest in participating in the RJV.[3] Firms may have different objectives and priorities with respect to the technological developments of their products. Some firms may prefer to stay out of the RJV and benefit from the research results of the RJV without sharing in the costs or providing information about its

[3]Branstetter and Sakakibara (1997) report that in Japan technology leaders are more reluctant to participate in some research consortia.

technology.[4] Antitrust authorities may pay more attention to cooperation between a large number of firms: an industry-wide RJV eliminates competition along the R&D dimension, which may lead to complacency in research efforts (Kamien and Zang, 1993). Finally, some firms may be more secretive about their R&D results, and refuse to participate in RJVs. It is then not surprising that in the real world, most RJVs involve only a subset of firms in a given industry.

The paper is organized as follows. The four-stage model is presented in section 2. The results are taken up in section 3 in terms of output and R&D, information sharing, cartel stability, technological diffusion, and profits and welfare. Section 4 concludes.

2. The model

There are T identical firms selling a homogeneous output, whose inverse demand is given by $p=a-wY$, $Y=\sum_{i=1}^{T} y_i$, where Y is total output and y_i is firm i's output. The unit cost of firm i is

$$c_i(\Gamma_i) = r - x_i - f \sum_{j \neq i}^{T} x_j - \Gamma_i \tag{1}$$

The parameter r is the production cost per unit before cost reductions attributable to R&D spending. The variable x_i is the R&D output of firm i. One unit of R&D reduces the production cost to its producer by one dollar and reduces the production cost of each of the other firms by f dollars, $f \in [0,1]$ being an (involuntary) exogenous spillover level. Γ_i represents the effect of voluntary information sharing on the cost of firm i. Note that Γ_i represents information received by, not information divulgated by, firm i. The parameters are assumed to be such that costs are strictly positive, that is,

$$r > x_i + f \sum_{j \neq i}^{T} x_j + \Gamma_i \tag{2}$$

The profit of firm i is

$$\pi_i = [p(Y) - c_i(\Gamma_i)] y_i - u x_i^2 \tag{3}$$

where the dollar cost of x units of R&D is ux^2, $u>0$.

The game has four stages. In the first stage the size of the RJV, M, is determined endogenously. The number of firms outside the RJV is $N=T-M$. Only one RJV is allowed to form. In the second stage insiders decide on g, the level of information sharing within the RJV. In the third stage each firm decides on its R&D output, x_i. RJV members coordinate R&D expenditures to maximize their joint profits, while outsiders act noncooperatively. In the final stage firms compete noncooperatively à la Cournot.

The sequence of decisions is linked to the logical sequence of the formation of a real RJV. Before participating in the RJV, firms decide on its structure. Two important elements of this structure are the size of the RJV and the level of information sharing within the RJV. The former is likely to be agreed upon before the latter, for it will be only participants that decide on the level of information sharing.

[4]For instance, the research results of SEMATECH (the Semiconductor Manufacturing Technology Consortium) benefited members as well as non-members of the research consortium (Grindley et al., 1994).

The first stage is the determination of the size of the RJV. For simplicity's sake, the total size of the industry, *T*, is given. Players are ranked according to an exogenous rule of order. Because firms are identical, the profitability of the RJV depends only on its size, and not on the identity of its members. This is equivalent to an anonymity condition: each player's payoff depends only on the number of players who choose each strategy (insider/outsider).[5] It is assumed that insiders can block the entry of an additional firm if it reduces their profits.[6] An outsider will join the RJV only if this increases its profits, and is allowed by insiders. I define stability of the RJV as follows:

Definition. Let $\pi_i^m(z)$ represent the profit of an insider, and $\pi_i^n(z)$ represent the profit of an outsider when the RJV is of size z. Then a RJV of size M is stable iff, for $M \geq 2$,

$$\begin{aligned} &i)\ \pi_i^m(M) \geq \pi_i^m(M\text{-}1) \text{ and} \\ &ii)\ \pi_i^m(M) \geq \pi_i^n(M\text{-}1) \text{ and} \\ &iii)\ \pi_i^m(M) \geq \pi_i^m(M+1), \text{ or } \pi_i^n(M) \geq \pi_i^m(M+1), \text{ or both.} \end{aligned} \tag{4}$$

Condition *i* states that RJV members would not gain by eliminating a firm from the RJV. Condition *ii* states that no member wants to drop unilaterally from the RJV (internal stability). Condition *iii* states that either no outsider wants to join the RJV (external stability), or insiders would lose by allowing an additional firm into the RJV, or both. When more than one RJV size satisfy (4), (4) is re-applied to those RJV sizes, except that profits are compared between stable coalitions, not by considering individual deviations (since these have already been taken care of in (4)). When more than one RJV size yield exactly the same profits for insiders and the same profits for outsiders (and that both satisfy (4)), the largest of these RJV sizes is assumed to prevail.

The stability conditions used here are different from those usually adopted in the cartel stability literature. De Bondt et al. (1992) and De Bondt and Wu (1997) use a Nash stability concept, based on d'Aspremont et al. (1983), which relies exclusively on internal and external stability, allowing for free entry into the cartel. Shaffer (1995) addresses the entry-blocking capacity of the cartel, but her stability concept incorporates only conditions *i* and *ii*. Poyago-Theotoky (1995) uses an entry-blocking cartel, but considers the condition $\pi_i^m(M) \geq \pi_i^m(M+1)$ as necessary, while here it is not. The concept used here incorporates internal and external stability, and goes further by allowing for entry-blocking by the cartel.[7]

We now turn to the second stage of the game, where insiders decide on information sharing. Cooperating firms may decide to share information beyond the basic spillover level, *f*. The cause to effect relationship between cooperation and spillovers is bidirectional: not only do spillovers affect the decision

[5] A common weakness of this approach to cartel stability is that, while it informs us about the stability of the cartel, it tells us very little about the process behind the formation of the cartel, or about the identity of its members.

[6] For instance, Combs (1993) reports that members of the Microelectronics and Computer Technology Corporation vote to allow a firm to purchase shares in the venture.

[7] RJVs are generally short-lived. Kogut (1989) shows that joint ventures are highly unstable. This instability is often due, in his words, to "business failure or a fundamental instability in governance." He finds that the stability of a joint venture increases with its R&D intensity. Bureth et al. (1997) note that the knowledge produced by pre-competitive research agreements (such as the one studied here) is highly generic and abstract, which reduces the cost of breaking with the cartel, thereby increasing instability.

to cooperate, but also the decision to cooperate affects spillovers.[8] Let $g \in [0,1\text{-}f]$ represent the level of voluntary information sharing within the RJV. The total (involuntary+ voluntary) information sharing level within the RJV is $f+g$.

There is an information leakage from the RJV to outsiders on voluntary information sharing within the RJV. It is the same information that is affected by voluntary information sharing and by exogenous spillovers, and the voluntary sharing in the first case is likely to affect the (involuntary) leakages in the second case. From the moment a firm decides to share some of its private information with one or more other firms , the firm takes the risk that this information may leak to third parties.[9] By transmitting the information to other RJV members, the probability of leakage increases.[10] While an in-house research project may be run in total secrecy, the very formation of a RJV and the type of research being performed is common knowledge, for it usually requires the government's approval. When RJV members know that their information sharing will increase spillovers to outsiders, they may wish to choose less than perfect information sharing. And outsiders, knowing this, will act strategically so as to benefit from this link.[11] The dependence of spillovers from the RJV to outsiders on information sharing, which is endogenous, makes those spillovers themselves endogenous to the model.

Let $k \in [0,1]$ represent the leakage factor from the RJV to outsiders on voluntary information sharing. The total spillover level from the RJV to outsiders is $f+kg$. Hence there are three types of spillovers: an exogenous spillover level applicable to all firms (f), an endogenous spillover level applicable within the RJV (g), and an exogenous spillover level from the RJV to outsiders (k). Figure 1 shows information flows. The following inequalities must hold: $0 \leq f \leq f+kg \leq f+g \leq 1$.

[Figure 1 here]

Let M be the number of RJV members (to be determined endogenously in the first stage), and let N be the number of outsiders, $M+N=T$. Without loss of generality assume that the first M firms join the RJV, while the other N firms remain outsiders. The following notation will be used to represent R&D output:

$$X^m \equiv \sum_{i=1}^{M} x_i^m \qquad \text{(Total R\&D output of the RJV)}$$
$$X_{-i}^m \equiv X^m - x_i^m$$
$$X^n \equiv \sum_{i=M+1}^{T} x_i^n \qquad \text{(Total R\&D output of outsiders)}$$
$$X_{-i}^n \equiv X^n - x_i^n$$

[8]Colombo and Garrone (1996), in their study of R&D and cooperation behaviour of 95 US, European, and Japanese firms, find that feedbacks between internal R&D and the participation in cooperative R&D agreements exist, and hence neither dimension can be considered exogenous with respect to the other.

[9]For instance, Mansfield (1985) finds that information on a new product or process is divulgated on average one year after its discovery.

[10]Cassiman and Veugelers (1998) find that cooperating firms have lower outgoing spillovers. However, that result is weakened by the fact that the data used gives information only on whether a given firm cooperates in R&D or not, without evidence on the extent of cooperation or on the nature of the cooperative agreement. Moreover, the data does not allow the separation of spillovers to and from partners versus non-partners. Also, they do not explain what mechanisms cooperating firms use to reduce outgoing spillovers, or why such mechanisms are not used by noncooperating firms.

[11]Even if the spillover on voluntary information sharing is high, outsiders may still suffer because of the lead time advantage of insiders. This advantage seems important, for instance, in the Microelectronics and Computer Technology Corporation RJV (Peck, 1986).

$$X \equiv X^m + X^n \qquad \text{(Total R\&D output)}$$
$$X_{-i} \equiv X - x_i$$

We now define Γ_i. The information received by firm i, Γ_i, can take two values, depending on whether the firm is an insider or an outsider.

$$\Gamma_i^m \equiv gX^m_{-i}\,, \qquad i=1,...,M$$
$$\Gamma_j^n \equiv kgX^m\,, \qquad j=M+1,...,T$$

Insiders benefit the most from voluntary information sharing if they receive more information than outsiders, that is, if $\Gamma_i^m > \Gamma_j^n$. It is useful to examine under what circumstances this inequality holds. Assume for this purpose that $x^n_{M+1}=...=x^n_T$, $x^m_1=...=x^m_M$ (this will be shown to hold in equilibrium). Then it is immediate that $\Gamma_i^m > \Gamma_j^n$ if and only if

$$M > \frac{1}{1-k} \tag{5}$$

We see that insiders are more likely to benefit from information sharing (by insiders) more than outsiders the larger the RJV, and the lower k is. The relation does not depend on g. Also, it is neither sufficient nor necessary for insiders to spend more on R&D in order to benefit more from voluntary information sharing.

On substituting Γ_i^m and Γ_j^n into (1) we obtain the unit costs of outsiders and insiders

$$\begin{aligned} c_i^m &= r - x_i^m - (f+g)X_{-i}^m - f\,X^n, \qquad i=1,...,M \\ c_j^n &= r - x_j^n - f\,X_{-j}^n - (f+kg)X^m, \qquad j=M+1,...,T \end{aligned} \tag{6}$$

In the second stage insiders choose the level of information sharing to solve the following problem (outsiders do not take any decision at this stage):

$$max_g \quad \Sigma_{i=1}^M \quad \pi_i^m = [p(Y(\Gamma)) - c_i^m(\Gamma_i^m)]y_i^m(\Gamma) - u[x_i^m(\Gamma)]^2 \tag{7}$$

where $\Gamma = \{\Gamma_1^m,...,\Gamma_M^m, \Gamma_{M+1}^n,...,\Gamma_T^n\}$.

In the third stage firms decide on R&D expenditures. Insiders choose their R&D expenditures to maximize their joint profits, while each outsider chooses its R&D to maximize its own profits. Let $x^n \equiv \{x^n_{M+1},...,x^n_T\}$, and $x^m \equiv \{x^m_1,...,x^m_M\}$. Outsider i solves the following problem

$$max_{x_i^n} \quad \pi_i^n = [p(Y(x^n,x^m)) - c_i^n(x^n,x^m)]y_i^n(x^n,x^m) - u[x_i^n]^2 \qquad i=M+1,...,T \tag{8}$$

and insiders solve, jointly

$$max_{x_1^m,...,\,x_M^m} \quad \Sigma_{i=1}^M \quad \pi_i^m = [p(Y(x^n,x^m)) - c_i^m(x^n,x^m)]y_i^m(x^n,x^m) - u[x_i^m]^2 \tag{9}$$

In the final stage (the output stage) firm i solves the following problem

$$max_{y_i} \quad \pi_i = [p(Y)-c_i(\Gamma_i)]y_i - ux_i^2 \qquad i=1,...,T \tag{10}$$

Note that output is chosen noncooperatively.

3. Results

We solve the model starting from the last stage to ensure subgame perfectness.

3.1 Output and R&D

Solving the output stage (10) yields each firm's output as a function of R&D expenditures of all firms and of spillovers:

$$y_i = \frac{a-r+(f+T(1-f))x_i+T\Gamma_i+(2f-1)X_{-i}-\Sigma_{j\neq i}^{T}\Gamma_j}{w(T+1)} \qquad i=1,...,T \tag{11}$$

Substituting Γ_i^m and Γ_i^n into (11) yields each outsider's output y_i^n and each insider's output y_i^m

$$\begin{aligned} y_i^n &= \frac{a-r+(f+T(1-f))x_i^n+(2f-1)X_{-i}^n+[2f-1+g(1+k-M(1-k))]X^m}{(T+1)w} \qquad i=M+1,...,T \\ y_i^m &= \frac{a-r+(f+g+M(1-f-g)+N(1-f-kg))x_i^m+(2f-1+g(2+N(1-k)))X_{-i}^m+(2f-1)X^n}{(T+1)w} \qquad i=1,...,M \end{aligned} \tag{12}$$

We now turn to the third stage, the determination of R&D expenditures. The simultaneous solving of the T first-order conditions resulting from (8) and (9) yields each insider's R&D, $x_i^m(a,w,M,N,r,u,f,g,k)$, $i=1,...,M$, and each outsider's R&D, $x_i^n(a,w,M,N,r,u,f,g,k)$, $i=M+1,...,T$.[12] The ex ante symmetry of firms implies that $x_{M+1}^n=...=x_T^n$, $x_1^m=...=x_M^m$.[13] From (12) it can be seen that this symmetry in R&D expenditures implies symmetry in output, that is, $y_{M+1}^n=...=y_T^n$, $y_1^m=...=y_M^m$.

3.2 Information sharing

The second stage is the determination of information sharing within the RJV. This requires solving (7). It turns out that even with the relatively simple functional forms used here no closed form solution exists for g, hence numerical simulations are used. The following numerical parametrization is adopted: a=1000, r=50, u=60, w=1, and T=10. Note that f and k have not been fixed, because we want to study their effect on the equilibrium. For that, in the remainder of this paper the solution is studied at f={0,0.1,...,1}, k={0,0.1,...,1}.

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[12] See Appendix.

[13] The Salant and Shaffer (1998) critique of the use of symmetric R&D strategies does not apply here, because there are no side payments and there is only one output market. Moreover, the very idea of side payments goes counter to the pre-competitive nature of R&D collaboration.

To derive the result we proceed as follows. We first fix M. Then, we consider all possible combinations of f and k. For every couple (f,k), we search, numerically, for g that maximizes insiders' profits. This exercise is repeated for all $M \in \{2,3,...,T\}$. We obtain g for all couples (f,k), for all $M \in \{2,3,...,T\}$.

Proposition 1. *For a given RJV size $M \in \{2,...,T\}$, there exists a critical leakage level $k_c \in (0,1]$ such that for all $k \leq k_c$ maximal information sharing is chosen ($g=1-f$) and for all $k > k_c$ no information is shared ($g=0$). Moreover, k_c is nondecreasing in M.*

Proposition 1 says that for a given RJV size, firms will choose maximal information sharing if k is smaller than a certain threshold, and will choose zero information sharing if k is higher than that threshold. The threshold k_c is nondecreasing in M. Information sharing is found to be either maximal or minimal, it never takes intermediate values. This implies that, everything else being equal, the relationship between insiders' profits and g is either positive or negative, it never changes sign with g. It is positive when $g=1-f$, and negative when $g=0$.

When $k=0$, voluntary information sharing within the RJV reinforces its competitive position relative to outsiders, without yielding any advantage to outsiders; hence insiders always choose maximal information sharing in this case. With $k>0$, some information leaks out, hence information sharing by insiders benefits both insiders and outsiders. Insiders choose maximal information sharing when k is sufficiently low so that the benefits leaking to outsiders are not too important. For large k, insiders do not share information, since outsiders benefit from it significantly at no cost. Clearly, for a given level of R&D, it is socially optimal that firms share all their research results. Hence a weak protection of cooperative research (i.e. a high k) will lead to suboptimal information sharing.

The leakage on voluntary information sharing represents a competitive impediment to information sharing. It is shown that this competitive impediment leads to extreme levels of information sharing. There exist other factors which may also affect information sharing. Technological impediments represent one such factor: the cost of sharing information, or imperfect compatibility of firms' technologies, can lead to intermediate levels of information sharing. The model predicts that the absence of information sharing is due to competitive impediments, while intermediate levels of information sharing are due to technological impediments.

The finding that firms choose extreme levels of information sharing (in the absence of technological impediments) is recurrent in the literature. Amir and Wooders (1999) analyse a research consortium composed of two firms which choose R&D and the spillover rate. However the spillover is one-directional: it flows only from one firm to the other firm. They find that firms choose extreme levels of information sharing. The rationale is that firms choose maximal information sharing when the efficiency effect -which pushes for cost minimization- dominates, while they choose no spillovers when the asymmetry effect -which pushes for maximum cost differentiation in order to maximize joint profits- dominates. Poyago-Theotoky (1999) allows firms to choose the spillover level after R&D investments are undertaken in a duopoly; she finds that cooperating (non-cooperating) firms choose maximal (minimal) spillovers.

Figure 2 depicts the relationship between the leakage factor on voluntary information sharing and RJV size. This figure reads as follows. For each RJV size, values of k lower or equal to the corresponding k_c entail maximal information sharing (g=1-f), and values of k higher than the corresponding k_c entail minimal information sharing (g=0). Hence, maximal information sharing is chosen below the curve $k_c(M)$, while minimal information sharing is chosen above that curve. For $M \geq 6$ firms always choose maximal information sharing. For $M \leq 6$, they minimize or maximize information sharing, depending on k. Moreover, f does not appear on this graph because it does not affect the decision of whether to share information or not.

[Figure 2 here]

The threshold k_c increases with M because as M increases the impact of information leakage on outsiders is less important (because there are less outsiders to benefit from it), and the benefits of internal information sharing increase (because there are more insiders). As k increases, a larger RJV becomes necessary to make information sharing in the RJV beneficial to insiders. This suggests that RJVs constrained in size (by regulation, for instance) are less likely to share information, or are likely to share less information, than non constrained RJVs, because of the benefits such sharing provides to outsiders.

Because small RJVs are less likely to share information, they need more protection than larger RJVs. Moreover, RJVs in markets where appropriability problems are important need more protection. Hence, it is sufficient to induce either a low k or a large M: either cooperative research is protected, which will induce larger RJVs, or incentives for larger RJVs are provided, in which case less protection is needed. This recommendation underlines a paradox when viewed from a dynamic point of view, however. Small RJVs need more protection. As this protection is provided, the size of the RJV is likely to increase. As the RJV becomes larger, the level of protection of the RJV necessary to induce its members to share information decreases. However, the temporary nature of most R&D agreements mitigates the importance of this dynamic inconsistency problem.

Also drawn on figure 2 is the curve k=1-1/M, which is derived from equation (5). On this curve $\Gamma_i^m = \Gamma_j^n$: insiders and outsiders receive exactly the same amount of cost reduction in dollars coming from voluntary information sharing (for insiders) and from the leakage on that voluntary information sharing (for outsiders). Below (above) the curve, insiders receive more (less) information than outsiders. For k sufficiently high, outsiders always receive more information, independently from M. Note that this curve lies below the function $k_c(M)$. This means that there is a parameter space (region B) where outsiders receive more cost reduction from voluntary information sharing (between insiders) than insiders, but where insiders still choose to share that information. In that case, even though outsiders benefit more (in terms of technological flows), insiders still increase their profits by sharing information. In region A, the information outsiders receive is so much higher than what insiders receive that information sharing would reduce insiders' profits, therefore insiders refrain from sharing information. In region C, insiders receive more information from voluntary information sharing, therefore they share the information. The fact that the function k=1-1/M, which is derived from the cost functions, has the same shape as $k_c(M)$, which is derived from numerical simulations, reinforces the results obtained from numerical simulations, and show the robustness of the general shape obtained for the function $k_c(M)$.

Corollary 1. *The decision of whether to share information or not depends on k, but is independent of f. The level of information sharing depends on f, but is independent of k.*

Corollary 1 states that the determinants of the decision to share information and the determinants of the level of information sharing are different. While the decision of whether to share information or not does not depend on *f*, the level of information sharing depends on *f*, because $g \leq 1-f$. At the same time, the decision to share information or not depends on *k*, but the level of information sharing is independent of *k*. However, while the level of information sharing is independent of *k*, the amount of information effectively shared is affected by *k*, since *k* affects R&D.

Information sharing within the RJV is socially desirable. Firms may in some circumstances choose suboptimal levels of information sharing. There is a well-known tradeoff between increasing the pace of innovation and inducing a high diffusion of the innovation.[14] The model points to a related effect of the lack of protection of cooperative innovations (high *k*): it may prevent firms from sharing information, hence reducing the diffusion of existing innovations. There is a tradeoff between the (voluntary) diffusion of the innovation to the immediate partners of the firm, and the (involuntary) diffusion of the innovation to other agents in the economy.

3.3 RJV size

Consider now the first stage of the game, the determination of the RJV size according to (4). The size of the RJV is determined by three effects: a coordination effect, an information sharing effect, and a competition effect. The coordination effect comes from the fact that an additional member increases the externalities internalized by the RJV. The information sharing effect comes from the possibility of improved information sharing among RJV members, discounted by any leakage of part or all of this information to outsiders. The competition effect comes from the fact that the newcomer is now a fiercer competitor on the output market.

From the point of view of insiders, the first two effects encourage an increase in the size of the RJV, while the third effect discourages increases in the size of the RJV. Moreover, there is an indirect link between the information sharing effect and the competition effect: because information sharing reinforces the competitive position of RJV members relative to outsiders, it reinforces the competition effect. From the point of view of an outsider considering whether to join the RJV or not, all three effects reinforce the profitability of joining the RJV.

The importance of each of these effects varies with *f*, *k*, and *M*. Consider first the effect of *f*. The coordination effect becomes more important as *f* increases, because more externalities are internalized. The information sharing effect becomes less important as *f* increases, because there is less scope for additional information sharing. The competition effect becomes less important as *f* increases because the advantage of the RJV over outsiders tends to diminish with spillovers; hence as *f* increases the scope for an improved competitive position of the newcomer is reduced.

Consider next the effect of *k*. With information sharing, the coordination effect declines with *k*: in that case coordination increases R&D, and the benefits of this increase decline with *k*. The information sharing effect becomes less important with *k* because higher leakage on voluntary information sharing reduces the value of additional information sharing to the RJV. The competition effect becomes less

[14]This result does not always hold empirically, however. As Baumol (1997) notes, innovation spillovers are higher in the Japanese economy than in the American economy, with no observable negative effects on Japanese innovation.

important with k, because the relative disadvantage of outsiders diminishes with k.

The importance of the three effects also varies with the size of the RJV. The coordination effect and the information sharing effect become negligible as M increases, because the marginal gain compared to existing coordination and information levels decreases. Regarding the competition effect, Bloch (1995) notes that it becomes more important as the size of the RJV increases: the cost reduction advantage of the RJV tends to increase with its size. The larger the RJV, the more inefficient is the newcomer, the more it gains from joining the RJV, and hence the stronger is the competition effect. On the other hand, when M is small, the RJV is only marginally more efficient than outsiders, hence the competition effect is less important.

We now determine the endogenous size of the RJV, M^*, which has to satisfy (4). For each couple (f,k) we determine M^* given that g is chosen according to proposition 1.

Proposition 2. *Generally, the size of the RJV* (M^*) *increases and then decreases with f, and increases and then decreases with k* (*see table* 1 *for exact results*).

The result of this algorithm is shown in table 1. In most cases, the RJV comprises more than half the industry, and in some few cases $M^*=T$. Overall there is an inverted U relationship between M^* and f: M^* increases and then decreases with f.[15] M^* first increases with f because the coordination effect increases, and the competition effect decreases, with f. M^* is low for high f because, as explained above, the information sharing effect (which encourages the formation of a larger RJV) becomes less important with f. Given that M^* is very small with high spillovers, it can be said that firms refrain from cooperation when it is most highly socially valued.

Consider next the effect of k. Overall there is an inverted U relationship between M^* and k: M^* increases and then decreases with k.[16] The size of the RJV may increase with the extent of the leakage from the RJV to outsiders (this is counterintuitive, since a higher k decreases the attractiveness of the RJV for both insiders and outsiders)[17] because the competition effect, which induces a smaller RJV, becomes less important as k increases. M^* decreases with k when k is high because the information sharing effect becomes negligible.

The size of the RJV can be less than the whole industry for two reasons: external stability, or blocking by insiders. Table 1 distinguishes between these two cases. When either f or k are low, the size of the RJV is constrained by blocking by insiders. In these cases, the coordination effect, which encourages larger RJVs, is small; and the competition effect, which encourages smaller RJVs, is large. On the other hand, when either f or k are high, the size of the RJV is constrained by external stability: outsiders are not interested in joining the RJV. This is because, as explained earlier, the attractiveness of the RJV to outsiders decreases with f and k.

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[15]Poyago-Theotoky (1995) finds that M^* increases steadily with f. This monotonous relation does not obtain here, because of the leakage on voluntary information sharing.

[16]For $f=1$ the result is invariant to k, because $f=1 \Rightarrow g=0$. This invariance will be true in all subsequent tables.

[17]For insiders, the value of sharing information -and therefore the attractiveness of the RJV- is reduced by k because a larger portion of the information proprietary to the RJV leaks out. For outsiders, the attractiveness of the RJV decreases with k because they obtain a larger portion of the information shared by insiders without having to join the RJV.

There is a strong link between the curve k=1-1/M of figure 2 and table 1. It is almost always when $\Gamma_i^m<\Gamma_j^n$ (regions A and B of figure 2, above the curve k=1-1/M) -i.e. when voluntary information sharing benefits outsiders more than insiders- that the size of the RJV is limited by external stability rather than by blockage by the RJV.

Table 2 shows M_w, the socially optimal size of the RJV, taking into account endogenous (and decentralized) information sharing decisions by firms. For a given k, M_w is nondecreasing in f. Similarly, for a given f, M_w is nondecreasing in k. M_w is nondecreasing in f and k because the benefit of the internalization of externalities increases with these externalities. By comparing tables 1 and 2 we see that in most cases the RJV is too small compared with the social optimum.[18] $M^*=M_w$ only in very special cases.

Table 2 shows that in some cases $M_w<T$ (remember that T=10). This is true for low f and/or low k (the fact that with high spillovers a RJV encompassing all firms in the industry is socially optimal is well understood. It is consistent with other findings in the literature, e.g. Poyago-Theotoky, 1995). This means that welfare increases, and then decreases, with the size of the RJV, when f and/or k are low. This reduction in welfare is linked to R&D spending. When spillovers are low, R&D by each insider increases, and then decreases, with the size of the RJV. This can be seen on figure 3, which shows the R&D output of insiders for different values of M: x_i^m increases, and then decreases, with M when spillovers are low.

[Figure 3 here]

The explanation is as follows. An increase in the size of the RJV induces two effects on R&D spending by insiders: an R&D-coordination effect, and an R&D-information sharing effect.[19] The R&D-coordination effect comes from the internalization of more externalities. It is negative when spillovers are low, and positive when spillovers are high (this is a standard result in the literature; see De Bondt, 1996). The R&D-information sharing effect comes from the increased value of R&D to insiders, given that they can share more information. The R&D-information sharing effect encourages R&D, for all levels of spillovers. With low spillovers the R&D-coordination effect induces less R&D, while the R&D-information sharing effect induces more R&D spending. As the size of the RJV increases, the (negative) R&D-coordination effect becomes more important (because more externalities are being internalized) relative to the R&D-information sharing effect, and R&D decreases. On the other hand, with high spillovers the two effects have a positive impact on R&D, x_i^m increases steadily with M, hence an industry-wide RJV is desirable. The benefits of information sharing explain why a RJV is socially desirable even when spillovers are low. The reduction in R&D when spillovers are low explains why the socially optimal size of the RJV is smaller than the industry.[20]

[18]While the model suggests that in many cases industry-wide RJVs are socially optimal, the potential for output collusion qualifies this result. The presence of outsiders limits the benefit to insiders from output collusion, and maintains a competitive pressure in the industry.

[19]We use the prefix R&D to distinguish these effects from those affecting the size of the RJV.

[20]De Bondt and Wu (1997) obtain a similar result. They find that, when information sharing is allowed, with high spillovers full cooperation is desirable, while with low spillovers welfare increases, and then decreases, with the size of the RJV. And they note: "As the size of the RJV increases, the tendency for research cartel members to restrict output begins to dominate incentives to expand resulting from better information-sharing". Poyago-Theotoky (1995), in a model with g=1-f, finds that an industry-wide RJV is always socially optimal. However, she defines social welfare as industry profits, while here I consider the sum of industry profits and consumer surplus.

3.4 Technological diffusion

Proposition 1 and corollary 1 in section 3.2 explained how information sharing is determined for a given RJV size. Now that the size of the RJV has been endogenized in section 3.3, we analyze information sharing in equilibrium. Table 3 shows g for all couples (f,k), given that M=M*. Maximal information sharing is chosen except for some high levels of f and k. There is a dynamic interaction between the choices of M and g: the level of g to be chosen in the second stage has a direct impact on the choice of M in the first stage. Because the likelihood of information sharing increases with M, firms tend to choose the size of the RJV so as to make maximal information sharing an equilibrium. This explains why firms almost always choose maximal information sharing. A higher level of information sharing increases the benefits from cooperation to insiders, and increases the attractiveness of the RJV to outsiders, thereby increasing the size of the RJV. And a larger RJV is more likely to share information. Hence information sharing and the endogenization of M reinforce each other and lead to larger RJVs and more information sharing.[21] The information sharing problem, and the leakage of information to outsiders, are partly resolved when firms can adjust the size of the RJV.[22]

Figure 4 shows voluntary and total diffusion when k=f and T=10. The size of the RJV is not constant on this figure, it is determined endogenously. Note the gradual and then abrupt decline in g as k increases. Total diffusion in the RJV is first invariant to k, and then decreases and increases with k. Diffusion decreases and then increases with f. Hence higher legal diffusion can lead to less effective diffusion. Total spillovers from the RJV to outsiders (f+kg) increase with f=k at a decreasing rate, until the point where g=0, where the slope becomes constant.

[Figure 4 here]

Whereas for a given M, only f affects the level of information sharing, and only k affects the decision whether to share information or not (corollary 1), both k and f affect the choice of g when M is endogenized through their effect on the choice of M, which in turn affects the choice of g. Through that effect, both k and f can be said to affect the level of information sharing and the decision whether to share information or not, indirectly.

Table 4 shows total effective cost reduction, which is the sum of cost reductions accruing from different sources, to all firms. Total effective cost reduction, Q, is given by
$Q = X[1+f(M^*+N\text{-}1)]+X^m[g(M^*+kN\text{-}1)]$. In general Q decreases with f and k: the disincentives of diffusion on innovators dominate the positive effects of diffusion on receivers. Figure 5 shows the decomposition of Q according to its sources in the case f=k. The decomposition is as follows:

Own cost effect = X
Involuntary spillovers = $f\,(M^*+N\text{-}1)X$

[21]Kesteloot and Veuglelers (1995) obtain a similar result in a two-firms repeated game model.
[22]De Bondt et al. (1992) conjecture that “If cooperation on R&D is accompanied with perfect spillovers, ... one would expect stability to be less problematic”. Here it is shown that stability problems do not vanish when information sharing is allowed.

Voluntary information sharing = $g(M^*-1)X^m$
Leakage from the RJV on voluntary information sharing = $kgNX^m$

[Figure 5 here]

Involuntary spillovers and voluntary sharing are the most important sources of cost reduction, with voluntary sharing dominating for low $f=k$ and involuntary spillovers dominating for high $f=k$. The own cost effect is less important, and diminishes further with spillovers. However, the own cost effect is the only source of cost reduction that is strictly positive for all levels of spillovers. Nonetheless, most cost reduction is due to diffusion, rather than to the use of the technology by the innovating firm. Finally, the cost reduction accruing to outsiders from the leakage from the RJV is negligible, even (and especially) when k is high. However, this negligible leakage has the non-negligible effect of reducing voluntary information sharing (as well as the own cost effect for insiders). Moreover, involuntary leakage (kg) is generally more important than what figure 5 suggests. This is because involuntary leakage is highest when f is low and k is high (but not high enough to stop insiders from sharing information). This case is not depicted on figure 5. Looking at total effective cost reduction (the upper bound of the graph), we see that even when accounting for diffusion, spillovers reduce total cost reduction (this is not necessarily true when $k \neq f$, however).

The possibility of improved information sharing affects total R&D mostly when spillovers are low. This is due to three factors. First, the scope for additional information sharing is large with low spillovers, but is much reduced when spillovers are already high. Second, with high spillovers, firms are more likely to choose not to share any information, because of leakage to outsiders. Third, for very high spillovers, the endogenous decline in the RJV size induces firms to choose not to share any additional information.

It is useful to separate the effects of R&D coordination and the effects of information sharing on welfare. Whereas the (social) benefits of R&D coordination are positively related to f, the (social and private) benefits of information sharing are negatively related to f. The intuition is as follows. R&D coordination internalizes an externality. When this externality is negative (f is low), firms reduce R&D. When this externality is positive (f is high), firms increase R&D. Hence society benefits from R&D coordination only when f is high. A different pattern emerges regarding the relation between the benefits of information sharing and f. The maximum amount of information firms can share voluntarily is that amount that does not leak out involuntarily, and this amount is inversely related to f.[23]

This result has implications for the regulation of R&D cooperation. Baumol (1992) argues that "The use of a technology cartel to collude on ... total R&D expenditures is likely to be damaging to public welfare." He is more open to technology cooperative agreements involving improved information sharing. A similar position is held by De Fraja (1990).[24] The model gives mixed recommendations

[23]Consistent with that result, Hinloopen (1994) and Greenlee (1998) find that RJVs which share information but do not coordinate R&D expenditures are welfare reducing when spillovers are high. This is due to the disincentives information sharing has on R&D when it is not coupled with R&D coordination.

[24]Fölster (1995) studies the effects of different types of R&D subsidies on R&D cooperation and spending for a sample of Swedish industrial firms. Some R&D subsidies require cooperation but allow firms to choose the mode and extent of information sharing (e.g. Eureka). Other R&D subsidies require cooperation and information sharing between participating firms (e.g. Esprit,

regarding the regulation of R&D cooperation. Contrarily to RJVs that coordinate R&D expenditures only, which are beneficial only when spillovers are high, and RJVs that share information only, which are beneficial only when spillovers are low (Hinloopen, 1994; Greenlee, 1998), RJVs that coordinate R&D expenditures and (may) share information improve welfare for all levels of spillovers. When spillovers are low, R&D coordination by itself reduces R&D, but this is more than compensated for by the increase in R&D due to information sharing. When spillovers are high, there is little scope for information sharing, but R&D coordination increases R&D. R&D coordination is beneficial if spillovers are high and/or firms share information. Also, combined with the results of Hinloopen (1994) and Greenlee (1998), the model suggests that information sharing is beneficial when spillovers are low (when spillovers are high information sharing is only marginally beneficial) and/or firms coordinate R&D expenditures.

3.5 R&D, profits, and welfare

Having determined RJV size and information sharing, we now analyze R&D and profits. Table 5 shows insiders' R&D. Again, M and g are not constant across this table: they are determined endogenously by firms for every level of f and k. As expected, x_i^m generally decreases with k and f, reaching a maximum at (0,0). Outsiders behave differently (table 6): x_i^n is decreasing in f, but increasing in k. A higher k increases the value of cost reduction to outsiders, increasing their R&D.

Tables 5 and 6 cannot be compared directly because the results are normalized so that $x_{i\ |(0,0)}=1$. Table 7 shows the ratio x_i^m/x_j^n. When k is low or moderate, $x_i^m>x_j^n$: insiders value R&D more, because they enjoy (the possibility of) improved information sharing, and internalize the externalities of their R&D on other insiders.[25] Outsiders free ride on insiders' R&D. When k is high, it is possible that $x_i^m<x_j^n$. The ratio decreases with k, but may increase or decrease with f.

The fact that information sharing within the RJV increases insiders' R&D implies that outsiders benefit from information sharing even when k=0, as long as f>0: when f is positive, outsiders obtain more spillovers from insiders through fx_i^m, because of the increase in x_i^m (which is due to information sharing). However, the net competitive effect of information sharing on outsiders may still be negative.

Table 8 shows insiders' profits. They generally decrease with f and k. In terms of technological flows (abstracting from R&D expenditures and RJV size, the effect of which is considered elsewhere in the paper), the information insiders receive from voluntary sharing is g, and the leakage to outsiders is kg. We saw that in equilibrium in most cases insiders choose maximal information sharing: g=1-f. Substituting g=1-f into the technological flows each group receives, and subtracting the second from the first to obtain the advantage of the RJV (when it shares information) over outsiders, we find that the advantage of the RJV is (1-f)(1-k). This advantage diminishes with both f and k. This explains why

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Race). Fölster finds that subsidy programs requiring only cooperation have no effect on the likelihood of cooperation but have a positive effect on R&D incentives. On the other hand, subsidy programs requiring both cooperation and information sharing increase the likelihood of cooperation, but decrease R&D incentives. He interprets the potential negative effect on R&D as a socially desirable elimination of duplication in research. Our model shows that this decline in R&D following cooperation can be due to at least two other factors: collusion between firms, and the desire to limit the amount of information leaking to competitors.

[25] Empirical evidence suggests that participation in research consortia has a positive impact on R&D expenditures (e.g. Branstetter and Sakakibara, 1997).

insiders' profits diminish with both the general spillover and the leakage on voluntary information sharing. In particular, spillovers hurt the RJV more than they hurt outsiders, because they reduce the possibility of information sharing. Even by adjusting their size and their information sharing to spillovers, insiders lose from *f and k*: π_i^m reaches a maximum at (0,0). Outsiders' profits (table 9) tend to increase with *f* when *k* is low and to decrease with *f* when *k* is high. They tend to increase, although not always, with *k*.

Table 10 compares insiders and outsiders' profits.[26] In most cases $\pi_i^m > \pi_j^n$. Insiders' profits are highest relative to outsiders' with (0,0). With low spillovers, insiders spend more on R&D, and a small portion of this R&D leaks out to competitors. Moreover, they may choose to increase information sharing, and only a small portion of this additional information sharing leaks out to outsiders. Hence insiders make more profits with low spillovers. When both *f* and *k* are high, $\pi_i^m < \pi_i^n$. This is also true when f=1. Even though insiders spend more on R&D than outsiders, the high level of spillovers, the small size of the RJV, and the limited scope for improving information sharing (remember that $g \leq 1\text{-}f$), result in a situation where outsiders benefit from this higher R&D output more than insiders.

Reading tables 1 and 10 together shows that, when the size of the RJV is limited by external stability, $\pi_i^m < \pi_i^n$. In contrast, when the size of the *RJV* is limited because of blockage by insiders, $\pi_i^m > \pi_j^n$. Also, there is a strong association between the curve k=1-1/M of figure 2 and table 10. It is almost always when $\Gamma_i^m < \Gamma_j^n$ (regions A and B of figure 2, above the curve k=1-1/M) -i.e. when voluntary information sharing benefits outsiders more than insiders- that insiders' profits are lower than outsiders'.

Table 11 shows the effect of *f* and *k* on total welfare. Overall welfare decreases with *f*, except with low *k* where it increases and then decreases with *f*. No clear trend can be detected for the effect of *k* on welfare. By reading this table jointly with table 1, we see that welfare is highest for those combinations of (*f*,*k*) that induce all firms to participate in the RJV. Those combinations yield the same level of total welfare even though *k* and *f* are different: *k* is irrelevant, because there are no outsiders; and *f* is irrelevant because firms choose maximal information sharing.

4. Conclusions

At the outset of the strategic investment literature the question was whether R&D cooperation is socially beneficial or not. Empirical and theoretical studies show that R&D cooperation is generally beneficial. Thus the question has now shifted to: what types of cooperation are superior, and which are likely to arise in a decentralized market? R&D cooperative ventures are complex multidimensional agreements. In this paper the focus was on RJV stability, information sharing, and leakage on voluntary information sharing.

The model studied information sharing and the stability of cooperation in cost reducing Research Joint Ventures (RJVs). In a four-stage game-theoretic framework, firms decided on participation in a RJV, information sharing, R&D expenditures, and output. An important feature of the model was that

[26]There is some empirical evidence that firms which cooperate on R&D obtain a higher rate of return on their research expenditures. For instance, Link and Bauer (1989), in the study of 92 US firms, found that the rate of return on R&D for firms engaging in cooperative R&D was 150 percent larger than for those that do not.

voluntary information sharing between cooperating firms increased information leakage from the RJV to outsiders. It was found that it is the spillover from the RJV to outsiders that determines the decision of insiders whether to share information or not, while it is the spillover affecting all firms that determines the level of information sharing within the RJV. RJVs representing a larger portion of the industry are more likely to share information. It was also found that firms never choose intermediate levels of information sharing: they share all the information or none at all. The model predicts that the absence of information sharing is due to competitive impediments (leakage of information to non-RJV members), while intermediate levels of information sharing would arise because of other considerations: costs of sharing information, or limited compatibility of firms' technologies. The size of the RJV was found to depend on three effects: a coordination effect, an information sharing effect, and a competition effect. Depending on the relative magnitudes of these effects, the size of the RJV may increase or decrease with spillovers. The effect of information sharing on the profitability of firms as well as on welfare was studied.

The sharpness of many of the results (e.g. no intermediary levels of information sharing; inverted U relationships between M and f on the one hand, and M and k on the other hand; different determinants of sharing information and of how much information to share) suggests that they are robust to changes in the numerical parametrization of the model. Numerical parametrization generally affects the magnitude of the results, not their qualitative nature.

The model focussed on the effect of leakage on voluntary information sharing on the level of information sharing. It was shown that this effect is most important when the RJV is small: large RJVs suffer less from leakages, and are less likely to stop sharing information because of them. The effect is also less important when spillovers are small. Because the maximum amount of information firms can share is the amount that is not already available through spillovers, information sharing is marginally beneficial when spillovers are high. Therefore leakages are less socially costly (even if they stop firms from sharing information) when spillovers are high.

The finding that firms share information when leakages are low and may not share it when leakages are high indicates that the imposition of no or maximal information sharing -both approaches are common in the literature- hides important assumptions. Studies that assume that cooperation firms do not share information implicitly assume that k is high, making information sharing unprofitable. Studies that assume maximal information sharing between firms implicitly assume that k is low.

By using a lax patent policy, the government gives firms the incentives to cooperate in order to internalize innovation externalities. And this formation of cooperative agreements may lead to information sharing. However, a problem with a lax patent policy aiming at inducing firms to cooperate is that firms may get the wrong message: instead of cooperating on R&D to internalize externalities and share information, firms may find it easier to move their research facilities to legislations (in a context where competition between legislations for R&D activities exists) providing a stricter protection for innovations, albeit with less R&D cooperation.

The scope for information sharing may be higher with newer technologies. Cooperation in industries with older, more mature technologies is likely to rely mainly on the coordination of R&D expenditures. This suggests that governments should favour RJVs in high-tech sectors. MITI (the Japanese Ministry of International Trade and Industry) seems to be following this path, with its focus on emerging technologies. In contrast, the British government funds cooperative research in mature declining industries.[27]

In this paper *k* was interpreted as a leakage parameter on information sharing. The mechanism behind this leakage was not specified. *k* can also be seen as a moral hazard parameter: once a firm has received information from other RJV members, it may have an incentive to trade part or all of that information with outsiders. While insiders may benefit from committing not to give information to third parties, such a commitment would not be credible. *k* can therefore represent the degree to which firms violate the secrecy of the RJV. In that respect, the results of the model suggest that firms may share information even in the presence of substantial moral hazard problems.

The model has many possible extensions. An interesting issue to explore is how information sharing is affected by product differentiation. Firms selling differentiated goods face less fierce competition on the product market, and may be more willing to share information. This intuition is confirmed by the observation that industry-wide joint ventures are observed more in countries where exports have a relatively greater importance than the domestic market (De Fraja, 1990). However, as product differentiation increases the information each firm possesses (or develops) may become less relevant to other firms.

The role of information leakage, *k*, could be explored further. *k* can depend on the size of the RJV: a larger RJV may leak out more information to outsiders than a smaller one. For instance, Link and Bauer (1989) find an inverse relation between appropriability of research results and the number of participants in research cooperative agreements.

In this paper firms were found to choose relatively high levels of information sharing. Many factors can make it difficult for firms to achieve such a high rate of diffusion of innovations. Information sharing may require the use of common research facilities, which brings into play diseconomies of scale. Increasing production costs would reduce the value of output expansion and hence of cost reduction. The high transaction costs of innovation may imply that RJVs are smaller than the model suggests, or that less information is shared because of opportunism. There may be a cost to sharing information, and that cost may rise with the size of the RJV; this would limit both RJV size and information sharing. When discoveries are made at different points in time, information exchange becomes more difficult; information sharing between firms could be made dependent on past experiences of information sharing. Differences in compatibility and communication, absorptive capacities, and organizational culture impose further limits on the levels (De Bondt et al., 1992) and the symmetry of information sharing.

Perhaps the main limit of this study is that firms can form only one RJV. Kamien and Zang study multiple RJV formation, with RJVs of identical sizes, although in their model information sharing is imposed upon firms. A more complete model of R&D cooperation would consider both endogenous information sharing and multiple RJV (of different sizes) formation. The socially optimal number of RJVs with endogenous information sharing is likely to be smaller than the socially optimal number of RJVs with exogenous perfect information sharing because, as our model shows, smaller RJVs are less likely to share information.

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[27] The reference for this insight is unfortunately lost.

Figure 1 - R&D spillovers

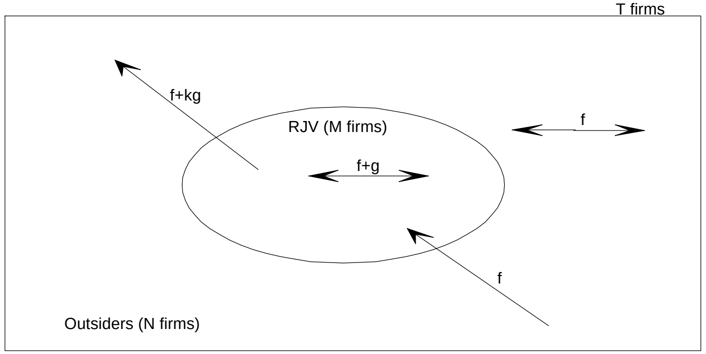

Figure 2 - Information sharing as a function of k and M

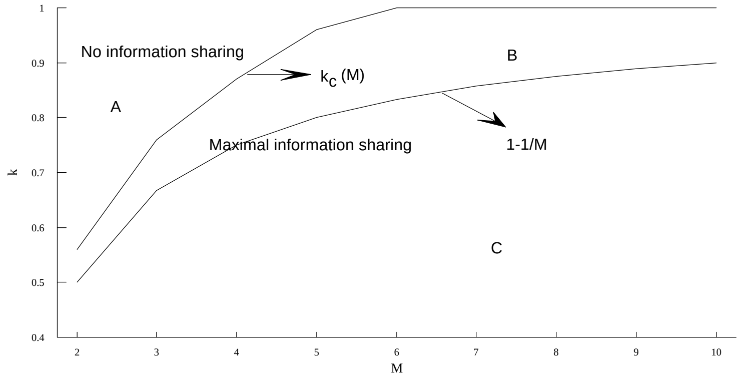

Figure 3 - Effect of M on insiders' R&D

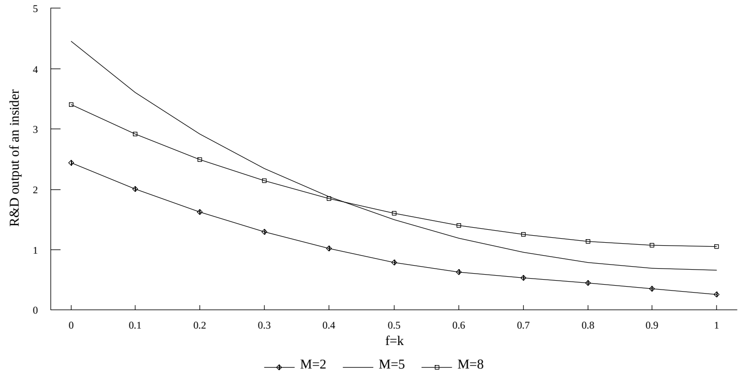

Figure 4 - Information sharing

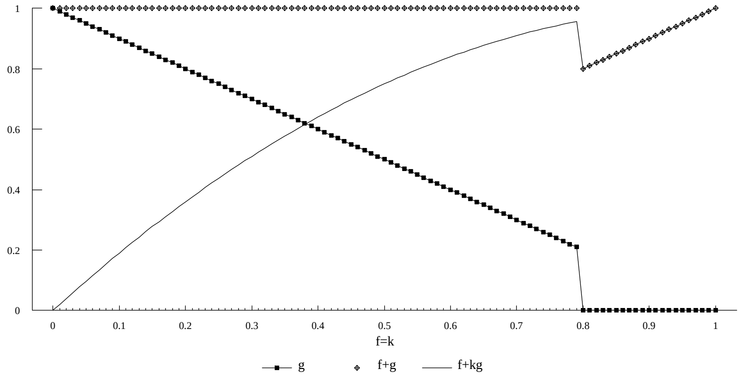

Figure 5 - Decomposition of cost reduction

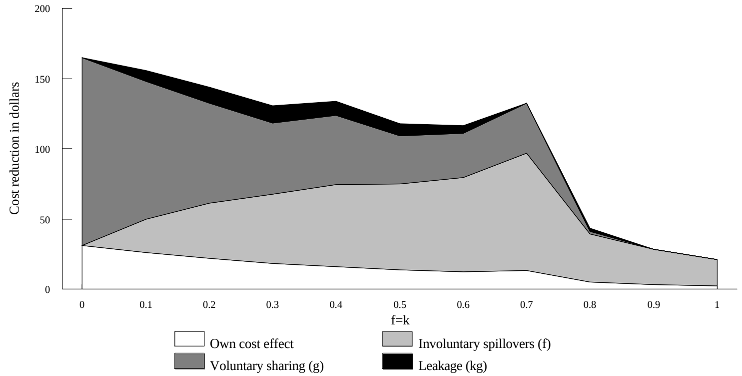

Table 1- Endogenous RJV size

f \ *k*	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	**6**	**6**	**6**	**6**	**6**	**7**	**7**	**8**	10	10	2
0.1	**6**	**6**	**6**	**6**	**6**	**7**	**7**	**8**	10	5	2
0.2	**6**	**6**	**6**	**6**	**6**	**7**	**7**	**8**	10	5	6
0.3	**6**	**6**	**6**	**6**	**6**	**7**	**7**	**8**	10	5	6
0.4	**6**	**6**	**6**	**6**	**7**	**7**	**7**	**8**	10	5	6
0.5	**6**	**6**	**6**	**6**	**7**	**7**	**8**	**8**	10	5	6
0.6	**6**	**6**	**6**	**7**	**7**	**7**	**8**	**9**	10	5	6
0.7	**6**	**7**	**7**	**7**	**7**	**8**	**9**	10	10	5	6
0.8	**7**	**7**	**8**	**8**	**8**	**9**	10	10	4	5	3
0.9	**9**	10	10	10	10	10	5	3	3	3	3
1	3	3	3	3	3	3	3	3	3	3	3

m: Blockage by RJV   m: external stability

Table 2- Socially optimal RJV size

f \ *k*	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	8	8	8	9	9	9	9	9	10	10	10
0.1	8	8	8	8	9	9	9	10	10	10	10
0.2	8	8	8	9	9	9	9	10	10	10	10
0.3	8	8	8	9	9	9	9	10	10	10	10
0.4	8	8	9	9	9	9	10	10	10	10	10
0.5	8	9	9	9	9	9	10	10	10	10	10
0.6	9	9	9	9	9	10	10	10	10	10	10
0.7	9	9	10	10	10	10	10	10	10	10	10
0.8	10	10	10	10	10	10	10	10	10	10	10
0.9	10	10	10	10	10	10	10	10	10	10	10
1	10	10	10	10	10	10	10	10	10	10	10

Table 3- Information sharing

f \ *k*	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	1	1	1	1	1	1	1	1	1	1	0
0.1	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0
0.2	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
0.3	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
0.4	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
0.6	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
0.7	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
0.8	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0
0.9	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0

Table 4- Total effective cost reduction

f \ *k*	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	164.97	158.77	151.43	142.98	133.43	145.45	131.64	131.10	132.68	132.68	12.84
0.1	162.30	155.85	148.48	140.20	131.02	141.55	128.85	128.85	132.68	56.82	22.28
0.2	157.91	151.37	144.11	136.13	127.42	136.85	125.29	126.12	132.68	59.27	59.38
0.3	151.72	145.28	138.27	130.71	122.59	131.33	120.97	122.93	132.68	60.62	61.56
0.4	143.64	137.48	130.91	123.92	133.78	124.97	115.87	119.26	132.68	60.87	62.87
0.5	133.62	127.94	121.97	115.71	125.33	117.76	122.40	115.12	132.68	60.02	63.32
0.6	121.59	116.60	111.42	122.05	115.94	109.68	116.39	122.82	132.68	58.08	62.90
0.7	107.52	119.60	115.00	110.32	105.57	114.30	122.51	132.68	132.68	55.04	61.62
0.8	107.17	103.98	114.71	111.77	108.81	120.04	132.68	132.68	43.57	50.92	34.03
0.9	119.29	132.68	132.68	132.68	132.68	132.68	50.07	29.88	28.43	28.43	28.43
1	20.98	20.98	20.98	20.98	20.98	20.98	20.98	20.98	20.98	20.98	20.98

Table 5- Insiders' R&D

f \ *k*	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	0.00	0.90	0.81	0.72	0.63	0.53	0.47	0.38	0.30	0.30	0.26
0.1	0.25	0.00	0.74	0.66	0.58	0.50	0.44	0.37	0.30	0.21	0.24
0.2	0.23	0.24	0.00	0.60	0.54	0.47	0.41	0.35	0.30	0.21	0.18
0.3	0.22	0.22	0.23	0.00	0.49	0.43	0.39	0.34	0.30	0.20	0.18
0.4	0.20	0.20	0.20	0.21	0.00	0.40	0.36	0.32	0.30	0.19	0.18
0.5	0.18	0.18	0.18	0.18	0.18	0.00	0.33	0.31	0.30	0.18	0.18
0.6	0.16	0.16	0.16	0.16	0.16	0.16	0.00	0.30	0.30	0.18	0.18
0.7	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.00	0.30	0.17	0.18
0.8	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.30	0.00	0.16	0.12
0.9	0.08	0.08	0.08	0.08	0.08	0.08	0.30	0.30	0.08	0.00	0.10
1	0.06	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09

Table 6- Outsiders' R&D

f \ *k*	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	28.38	1.04	1.08	1.11	1.13	1.14	1.16	1.18			1.19
0.1	25.76	23.81	1.00	1.02	1.04	1.05	1.07	1.07		1.10	1.09
0.2	23.22	21.55	19.94	0.94	0.95	0.95	0.96	0.97		0.99	0.99
0.3	20.76	19.35	17.97	16.63	0.85	0.85	0.86	0.87		0.88	0.88
0.4	18.36	17.18	16.03	14.90	14.74	0.75	0.76	0.76		0.77	0.77
0.5	16.00	15.05	14.11	13.19	13.31	12.39	0.65	0.66		0.66	0.66
0.6	13.70	12.95	12.21	12.62	11.88	11.15	11.32	0.55		0.55	0.55
0.7	11.43	12.12	11.57	11.01	10.47	10.95	11.41			0.44	0.44
0.8	10.51	10.14	10.89	10.58	10.26	11.10			4.39	0.34	0.33
0.9	10.99						4.73	2.89	2.85	2.85	0.23
1	1.91	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12

Table 7- insiders' R&D over outsiders' R&D *k*

		0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
	0	4.06	3.51	3.04	2.63	2.26	1.90	1.62	1.32			0.90
	0.1	3.87	3.40	2.98	2.61	2.27	1.94	1.67	1.39		0.79	0.91
	0.2	3.73	3.32	2.94	2.60	2.29	1.99	1.74	1.48		0.85	0.72
	0.3	3.63	3.27	2.93	2.62	2.33	2.06	1.82	1.59		0.92	0.82
	0.4	3.57	3.25	2.95	2.66	2.39	2.16	1.93	1.73		1.01	0.93
f	0.5	3.55	3.27	2.99	2.73	2.51	2.29	2.08	1.92		1.13	1.09
	0.6	3.59	3.33	3.09	2.90	2.69	2.49	2.34	2.22		1.30	1.30
	0.7	3.69	3.55	3.35	3.16	2.97	2.86	2.77			1.55	1.62
	0.8	4.09	3.93	3.85	3.72	3.59	3.58			1.77	1.96	1.43
	0.9	5.28						3.16	1.91	1.84	1.84	1.84
	1	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00

Table 8- Insiders' profits *k*

		0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
	0	1.0000	0.9783	0.9593	0.9426	0.9281	0.9158	0.9067	0.8997	0.8965	0.8965	0.8745
	0.1	0.9809	0.9637	0.9484	0.9349	0.9231	0.9131	0.9054	0.8995	0.8965	0.8816	0.8784
	0.2	0.9642	0.9507	0.9387	0.9279	0.9184	0.9104	0.9041	0.8992	0.8965	0.8841	0.8837
	0.3	0.9495	0.9392	0.9299	0.9215	0.9140	0.9078	0.9027	0.8987	0.8965	0.8862	0.8857
	0.4	0.9367	0.9290	0.9220	0.9156	0.9098	0.9053	0.9013	0.8982	0.8965	0.8878	0.8873
f	0.5	0.9255	0.9200	0.9149	0.9102	0.9063	0.9029	0.8997	0.8976	0.8965	0.8890	0.8886
	0.6	0.9158	0.9120	0.9085	0.9055	0.9029	0.9004	0.8984	0.8970	0.8965	0.8897	0.8895
	0.7	0.9074	0.9053	0.9033	0.9014	0.8997	0.8983	0.8971	0.8965	0.8965	0.8901	0.8901
	0.8	0.9010	0.8998	0.8988	0.8980	0.8972	0.8967	0.8965	0.8965	0.8897	0.8900	0.8890
	0.9	0.8967	0.8965	0.8965	0.8965	0.8965	0.8965	0.8905	0.8884	0.8883	0.8883	0.8883
	1	0.8870	0.8870	0.8870	0.8870	0.8870	0.8870	0.8870	0.8870	0.8870	0.8870	0.8870

Table 9- Outsiders' profits *k*

		0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
	0	1.0000	1.0850	1.1614	1.2291	1.2880	1.3034	1.3562	1.3859			1.4251
	0.1	1.0845	1.1537	1.2158	1.2708	1.3188	1.3297	1.3734	1.3969		1.4518	1.4311
	0.2	1.1604	1.2153	1.2646	1.3084	1.3465	1.3537	1.3891	1.4073		1.4531	1.4622
	0.3	1.2276	1.2699	1.3079	1.3416	1.3711	1.3753	1.4033	1.4170		1.4540	1.4618
	0.4	1.2861	1.3174	1.3455	1.3706	1.3698	1.3946	1.4160	1.4261		1.4547	1.4613
f	0.5	1.3359	1.3578	1.3776	1.3953	1.3935	1.4116	1.4173	1.4345		1.4550	1.4607
	0.6	1.3769	1.3913	1.4042	1.4000	1.4138	1.4262	1.4298	1.4371		1.4551	1.4600
	0.7	1.4094	1.4026	1.4128	1.4222	1.4307	1.4318	1.4356			1.4548	1.4592
	0.8	1.4241	1.4297	1.4275	1.4339	1.4399	1.4418			1.4515	1.4542	1.4487
	0.9	1.4410						1.4525	1.4484	1.4479	1.4479	1.4479
	1	1.4464	1.4464	1.4464	1.4464	1.4464	1.4464	1.4464	1.4464	1.4464	1.4464	1.4464

Table 10- Insiders' profits over outsiders' profits *k*

		0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
	0	1.6289	1.4687	1.3454	1.2493	1.1738	1.1446	1.0890	1.0574			0.9996
	0.1	1.4734	1.3607	1.2707	1.1983	1.1401	1.1186	1.0739	1.0488		0.9892	0.9997
	0.2	1.3535	1.2743	1.2090	1.1552	1.1109	1.0955	1.0602	1.0407		0.9911	0.9845
	0.3	1.2599	1.2047	1.1581	1.1188	1.0858	1.0752	1.0478	1.0331		0.9927	0.9869
	0.4	1.1864	1.1487	1.1161	1.0881	1.0819	1.0574	1.0367	1.0259		0.9941	0.9891
f	0.5	1.1285	1.1036	1.0817	1.0625	1.0593	1.0418	1.0340	1.0192		0.9952	0.9909
	0.6	1.0833	1.0678	1.0538	1.0536	1.0402	1.0284	1.0235	1.0166		0.9960	0.9924
	0.7	1.0487	1.0514	1.0414	1.0324	1.0243	1.0219	1.0178			0.9966	0.9936
	0.8	1.0305	1.0251	1.0256	1.0201	1.0149	1.0131			0.9984	0.9969	0.9996
	0.9	1.0136						0.9986	0.9991	0.9993	0.9993	0.9993
	1	0.9989	0.9989	0.9989	0.9989	0.9989	0.9989	0.9989	0.9989	0.9989	0.9989	0.9989

Table 11- Welfare *k*

		0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
	0	1.0000	1.0004	1.0004	1.0002	0.9996	1.0032	1.0014	1.0023	1.0038	1.0038	0.9790
	0.1	1.0013	1.0014	1.0012	1.0007	1.0000	1.0030	1.0013	1.0021	1.0038	0.9888	0.9813
	0.2	1.0021	1.0019	1.0016	1.0010	1.0001	1.0027	1.0010	1.0018	1.0038	0.9895	0.9897
	0.3	1.0024	1.0021	1.0015	1.0008	0.9999	1.0021	1.0006	1.0014	1.0038	0.9900	0.9903
	0.4	1.0022	1.0017	1.0011	1.0003	1.0026	1.0013	1.0000	1.0009	1.0038	0.9902	0.9907
f	0.5	1.0015	1.0009	1.0002	0.9994	1.0015	1.0003	1.0015	1.0003	1.0038	0.9902	0.9909
	0.6	1.0002	0.9996	0.9989	1.0010	1.0001	0.9991	1.0005	1.0019	1.0038	0.9899	0.9909
	0.7	0.9983	1.0007	1.0000	0.9992	0.9985	1.0002	1.0018	1.0038	1.0038	0.9894	0.9907
	0.8	0.9987	0.9982	1.0002	0.9997	0.9993	1.0014	1.0038	1.0038	0.9872	0.9886	0.9853
	0.9	1.0012	1.0038	1.0038	1.0038	1.0038	1.0038	0.9884	0.9846	0.9843	0.9843	0.9843
	1	0.9828	0.9828	0.9828	0.9828	0.9828	0.9828	0.9828	0.9828	0.9828	0.9828	0.9828

Appendix

R&D output

Let

$$
\begin{aligned}
q = {} & \\
& -f+3f^2-3f^3+f^4+2fg-4f^2g+2f^3g-fg^2+f^2g^2-M+4fM-8f^2M+8f^3M-3f^4M+2gM-8fgM+12f^2gM-6f^3gM-g^2M+4fg^2M \\
& -3f^2g^2M-2fM^2+6f^2M^2-7f^3M^2+3f^4M^2-2gM^2+8fgM^2-12f^2gM^2+6f^3gM^2+2g^2M^2-5fg^2M^2+3f^2g^2M^2-f^2M^3+2f^3M^3 \\
& -f^4M^3-2fgM^3+4f^2gM^3-2f^3gM^3-g^2M^3+2fg^2M^3-f^2g^2M^3-N+3fN-4f^2N+3f^3N-f^4N+2gN-4fgN+4f^2gN-2f^3gN-g^2N+fg^2N \\
& -f^2g^2N-MN+fMN+2f^2MN-4f^3MN+2f^4MN+2fgMN-5f^2gMN+4f^3gMN+g^2MN-fg^2MN+2f^2g^2MN+fgkMN-f^2gkMN \\
& -fg^2kMN-fM^2N+f^2M^2N+f^3M^2N-f^4M^2N-2gM^2N+3fgM^2N-2f^3gM^2N+g^2M^2N-fg^2M^2N-f^2g^2M^2N+gkM^2N-2fgkM^2N \\
& +2f^2gkM^2N-g^2kM^2N+2fg^2kM^2N-fgM^3N+f^2gM^3N-g^2M^3N+fg^2M^3N+fgkM^3N-f^2gkM^3N+g^2kM^3N-fg^2kM^3N-N^2+3fN^2 \\
& -4f^2N^2+3f^3N^2-f^4N^2+2gN^2-4fgN^2+4f^2gN^2-2f^3gN^2-g^2N^2+fg^2N^2-f^2g^2N^2-2fMN^2+5f^2MN^2-4f^3MN^2+f^4MN^2 \\
& -2gMN^2+7fgMN^2-9f^2gMN^2+4f^3gMN^2+2g^2MN^2-3fg^2MN^2+3f^2g^2MN^2+gkMN^2-2fgkMN^2+3f^2gkMN^2-2f^3gkMN^2 \\
& -g^2kMN^2+fg^2kMN^2-2f^2g^2kMN^2-3fgM^2N^2+5f^2gM^2N^2-2f^3gM^2N^2-g^2M^2N^2+3fg^2M^2N^2-3f^2g^2M^2N^2+3fgkM^2N^2 \\
& -5f^2gkM^2N^2+2f^3gkM^2N^2+g^2kM^2N^2-3fg^2kM^2N^2+4f^2g^2kM^2N^2-f^2g^2k^2M^2N^2-fg^2M^3N^2+f^2g^2M^3N^2+2fg^2kM^3N^2 \\
& -2f^2g^2kM^3N^2-fg^2k^2M^3N^2+f^2g^2k^2M^3N^2-fN^3+3f^2N^3-3f^3N^3+f^4N^3+2fgN^3-4f^2gN^3+2f^3gN^3-fg^2N^3+f^2g^2N^3-2fgMN^3 \\
& +4f^2gMN^3-2f^3gMN^3+2fg^2MN^3-2f^2g^2MN^3+2fgkMN^3-4f^2gkMN^3+2f^3gkMN^3-2fg^2kMN^3+2f^2g^2kMN^3-fg^2M^2N^3 \\
& +f^2g^2M^2N^3+2fg^2kM^2N^3-2f^2g^2kM^2N^3-fg^2k^2M^2N^3+f^2g^2k^2M^2N^3+uw-ufw-2ugw+2ufgw+ug^2w+2uMw-2uf^2Mw \\
& -2ufgMw-ug^2Mw+2uM^2w-ufM^2w+2ugM^2w-2ufgM^2w-ug^2M^2w+uM^3w-2ufM^3w+2uf^2M^3w+2ufgM^3w+ug^2M^3w \\
& +4uNw-7ufNw+4uf^2Nw-6ugNw+6ufgNw+3ug^2Nw+5uMNw-4ufMNw+2ugMNw-6ufgMNw-4ug^2MNw \\
& -2ugkMNw+2ufgkMNw+2ug^2kMNw+2uM^2Nw-ufM^2Nw+4ugM^2Nw-2ufgM^2Nw-ug^2M^2Nw-2ugkM^2Nw+2ufgM^3Nw \\
& +2ug^2M^3Nw-2ufgkM^3Nw-2ug^2kM^3Nw+4uN^2w-7ufN^2w+4uf^2N^2w-6ugN^2w+6ufgN^2w+3ug^2N^2w+2uMN^2w \\
& -2uf^2MN^2w+4ugMN^2w-6ufgMN^2w-5ug^2MN^2w-4ugkMN^2w+4ufgkMN^2w+4ug^2kMN^2w+2ugM^2N^2w+ug^2M^2N^2w \\
& -2ugkM^2N^2w-2ug^2kM^2N^2w+ug^2k^2M^2N^2w+ug^2M^3N^2w-2ug^2kM^3N^2w+ug^2k^2M^3N^2w+uN^3w-ufN^3w-2ugN^3w+2ufgN^3w \\
& +ug^2N^3w+2ugMN^3w-2ufgMN^3w-2ug^2MN^3w-2ugkMN^3w+2ufgkMN^3w+2ug^2kMN^3w+ug^2M^2N^3w-2ug^2kM^2N^3w \\
& +ug^2k^2M^2N^3w-u^2w^2-3u^2Mw^2-3u^2M^2w^2-u^2M^3w^2-3u^2Nw^2-6u^2MNw^2-3u^2M^2Nw^2-3u^2N^2w^2-3u^2MN^2w^2-u^2N^3w^2
\end{aligned}
$$

Then

$$
x_i^n = \frac{\begin{aligned}&[1+N+f^2(1-M+N)+g^2(1-M+kM)(1-M+N-MN+kMN)-g(2-2M+kM+2N-2MN+2kMN)\\ &+f(-2+M-2N+g(2-3M+kM+M^2-kM^2+2N-2MN+2kMN))-uw-uMw-uNw](-M-N+f(-1+M+N))(r-a)\end{aligned}}{q}
$$

for $i=M+1,\ldots,T$, and

$$
x_i^m = \frac{(1+f(-1+M-N)+N+g(-1+M-N+MN-kMN))(a-r)(M+f(1-2M-2N)+N+f^2(-1+M+N)-uw-uMw-uNw)}{q}
$$

for $i=1,\ldots,M$.

Strategic interaction of research efforts

The study of the strategic interaction of research efforts helps to illustrate the basic structure of the model, and will show how it compares with existing work.[28] As Becker and Peters (1995) note, "the incentives to create knowledge spillovers are always larger for strategic complements than for strategic substitutes". A standard result in the literature is that research efforts are strategic complements (substitutes) when spillovers are higher (lower) than a certain threshold. The basic intuition is that when

[28]Following Bulow et al. (1985) actions *a* and *b* are strategic complements if $\partial^2\pi/\partial a\,\partial b>0$, and are strategic substitutes if $\partial^2\pi/\partial a\,\partial b<0$.

spillovers are low, the externality on other firms is negative: an increase in research by firm *i* hurts firm *j*, which reduces its R&D. When spillovers are high, the externality is positive: an increase in research by firm *i* benefits firm *j*, which increases its R&D. This intuition applies for a homogeneous good industry with linear demand and (exogenous) industry-wide cooperation,[29] when firms produce in demand-unrelated industries (Steurs, 1995), when the size of the RJV is endogenous (Poyago-Theotoky, 1995), and when firms are vertically related (Atallah, 2000). While the threshold may change across market settings, the intuition remains the same.

In the model studied here, where the size of the RJV is endogenous and where spillovers between the RJV and outsiders are asymmetric and endogenous, the same intuition applies, but the result is more complex. There are four thresholds, determining the strategic interaction between outsiders and insiders, between insiders, and between outsiders.

Proposition 3.
i) $sign(\partial^2\pi_i^m/\partial x_i^m\,\partial x_j^n) = sign(f-\tfrac{1}{2})$.
ii) $sign(\partial^2\pi_j^n/\partial x_j^n\,\partial x_i^m) = sign(-1+2f+g(1+k-M(1-k)))$.
iii) $sign(\partial^2\pi_j^m/\partial x_j^m\,\partial x_i^m) = sign(-1+2f+g(2+N(1-k)))$.
iv) $sign(\partial^2\pi_j^n/\partial x_j^n\,\partial x_i^n) = sign(f-\tfrac{1}{2})$.

Proof. On substituting (12), Γ_i^m, and Γ_i^n into (3) and differentiating, we find that
i.

$$\frac{\partial^2\pi_i^m}{\partial x_i^m \partial x_j^n} = -\frac{2(-1+2f\ )[-T+f(T-1)+g(M+kN-1)]}{w(T+1)^2}$$

Since the term in brackets is negative, this expression takes the sign of $f-\tfrac{1}{2}$.
ii.

$$\frac{\partial^2\pi_j^n}{\partial x_j^n \partial x_i^m} = \frac{2(-1+2f+g(1+k-M(1-k)))[T-f(T-1)]}{w(T+1)^2}$$

Since the term in brackets is positive, this expression takes the sign of
$-1+2f+g(1+k-M(1-k))$.

iii.

$$\frac{\partial^2\pi_j^m}{\partial x_j^m \partial x_i^m} = -\frac{2(-1+2f+g(2+N(1-k)))[-T+f(T-1)+g(M+kN-1)]}{w(T+1)^2}$$

Since the term in brackets is negative, this expression takes the sign of $-1+2f+g(2+N(1-k))$.

[29]See De Bondt, 1996.

iv.

$$\frac{\partial^2 \pi_j^n}{\partial x_j^n \partial x_i^n} = \frac{2(-1+2f)[-T+f(T-1)]}{w(T+1)^2}$$

Since the term in brackets is negative, this expression takes the sign of $f-\frac{1}{2}$. ■

Parts *i* and *iv* of proposition 3 state that an increase in R&D expenditures by an outsider will increase R&D by other outsiders, and by insiders, if $f>\frac{1}{2}$, and will reduce it if $f<\frac{1}{2}$. A higher *f* means that the increase in x_i^n benefits all other firms substantially, which increases the value of cost reduction for them, and induces them to increase R&D. Note that the threshold obtained for these two cases is the same as that obtained in most studies.

Part *ii* states the condition which must be satisfied for an outsider to respond positively to an increase in R&D by an insider. The result depends on *f*, *k*, *g*, and *M*. The response is more likely to be positive when *f* is higher; the explanation is the same as above. It is also more likely to be positive when *k* is higher. This is because a higher *k* means that outsiders benefit more from the increase in R&D by an insider. The effect of *g* is positive when *k* is high, and negative when *k* is low. This is because a higher *g* benefits outsiders insofar as information leakage (*k*) on this additional information sharing is important. Finally, the effect of *M* is negative: the higher *M*, the lower is the benefit of outsiders relative to the benefit of insiders. *M* has an effect only insofar as $g>0$.[30] Numerical simulations (taking into account the optimization by firms with respect to *M* and *g*) show that in most cases insiders' and outsiders' R&D expenditures are strategic substitutes, except when *f* or *k* are high.

Part *iii* of proposition 3 states the condition that must be satisfied for an insider to respond positively to an increase in R&D by another insider. This response is more likely to be positive the higher *f*, *g*, *N*, and the lower *k*. The role of *f* is well understood. A higher *g* means that the externality is positive. The lower *k*, the greater is the benefit of insiders relative to the benefit of outsiders, and the more likely is the response to be positive. A larger *N* increases the likelihood that x_i^m and x_j^m are strategic complements. *N* has an effect only insofar as $g>0$. Numerical simulations show that in most cases insiders' R&D expenditures are strategic complements, except when *f* is low and *k* is very high.

Note that because of information sharing, insiders' R&D expenditures are more likely to be strategic complements than outsiders'. This can be seen from the fact that the term in part *iii* of proposition 3 is more likely to be positive than the term in part *iv*. This is due specifically to information sharing, *not* to R&D coordination: when $g=0$ the two conditions are equivalent.

[30] By setting $k=0$ and $g=1-f$ we obtain the special case studied by Poyago-Theotoky (1995) who finds that outsiders respond positively to an insider's increase in R&D if $f>M/(M+1)$.

Bibliography

Adams, J.D., 2000, *Endogenous R&D Spillovers and Industrial Research Productivity*, Working Paper 7484, NBER.

Amir, R., and Wooders, J., 1999, 'Effects of One-way Spillovers on Market Shares, Industry Prices, Welfare, and R&D Cooperation', *Journal of Economics and Management Strategy*, 8(2):223-49.

Atallah, G., 2000, *Essays on Vertical Integration, Vertical R&D Spillovers, Research Joint Ventures, and Information Sharing*, Ph.D. Thesis, Université de Montréal.

Baumol, W.J., 1992, 'Horizontal Collusion and Innovation', *Economic Journal*, 102:129-37.

Baumol, W.J., 1997, *Pareto Optimal Sizes of Innovation Spillovers*, Research Report # 97-42, The C.V. Starr Centre for Applied Economics, Department of Economics, New York University.

Becker, W., and Peters, J., 1995, *R&D-Competition between Vertical Corporate Networks: Structure, Efficiency and R&D-Spillovers*, Working Paper No. 144, Institut für Volkswirtshaftslehre, Universität Augsburg.

Bhattacharya, S., Glazer, J., and Sappington, D.E.M., 1990, 'Sharing Productive Knowledge in Internally Financed R&D Contests', *Journal of Industrial Economics*, 39(2):187-208.

Bhattacharya, S., Glazer, J., and Sappington, D.E.M., 1992, 'Licensing and the Sharing of Knowledge in Research Joint Ventures', *Journal of Economic Theory*, 56:43-69.

Bloch, F., 1995, 'Endogenous structures of association in oligopolies', *RAND Journal of Economics*, 26(3):537-56.

Branstetter, L., and Sakakibara, M., 1997, *Japanese Research Consortia: a Microeconometric Analysis of Industrial Policy*, Working Paper 6066, NBER.

Bulow, J.I., Geanakoplos, J.D., and Klemperer, P.D., 1985, 'Multimarket Oligopoly: Strategic Substitutes and Complements', *Journal of Political Economy*, 93(3):488-511.

Bureth, A., Wolff, S., and Zanfei, A., 1997, 'The two faces of learning by cooperating: The evolution and stability of inter-firm agreements in the European electronics industry', *Journal of Economic Behavior & Organization*, 32:519-37.

Cassier, M., and Foray, D., 1999, 'La régulation de la propriété intellectuelle dans les consortiums de recherche: les types de solutions élaborées par les chercheurs', *Economie Appliquée*, 52(2):155-82.

Cassiman, B., and Veugelers, R., 1998, *R&D Cooperation and Spillovers: Some Empirical Evidence*, Working paper, Universitat Pompeu Fabra/Katholieke Universiteit Leuven.

Cohen and Levinthal, 1989, 'Innovation and Learning: The Two Faces of R&D', *The Economic Journal*, 99:569-96.

Colombo, M.G., and Garrone, P., 1996, 'Technological cooperative agreements and firm's R&D intensity. A note on causality relations', *Research Policy*, 25(6):923-32.

Combs, K.L., 1986, *A Summary of Research Joint Ventures Filed with the Justice Department*, unpublished mimeograph.

Combs, K.L., 1993, 'The role of information sharing in cooperative research and development', *International Journal of Industrial Organization*, 11:535-51.

d'Aspremont, C., and Jacquemin, A, 1983, 'On the stability of collusive price leadership', *Canadian Journal of Economics*, 16(1):17-25.

d'Aspremont, C., and Jacquemin, A., 1988, 'Cooperative and noncooperative R&D in duopoly with spillovers', *AER*, 78:1133-37.

d'Aspremont, C., Bhattacharya, S., and Gérard-Varet, L.A., 1996, *Bargaining and Sharing Knowledge*, Discussion Paper No. TE/96/293, Suntory and Toyota International Centres for Economics and

Related Disciplines, London School of Economics and Political Science.

De Bondt, R., 1996, ‘Spillovers and innovative activities’, *International Journal of Industrial Organization*, 15:1-28.

De Bondt, R., Wu, C., and Lievens, D., 1992, *Stable Strategic R&D Cartels*, Onderzoeksrapport NR. 9204, Departement Toegepaste Economische Wetenschappen, Katholieke Universiteit Leuven.

De Bondt, R., and Wu, C., 1997, ‘Research Joint Venture Cartels and Welfare’, in Poyago-Theotoky (ed.), *Competition, Cooperation, Research and Development*, MacMillan, London.

De Fraja, G., 1990, *Strategic Disclosure of R&D Knowledge and Research Joint Ventures*, Discussion Paper No. 90/278, University of Bristol.

De Fraja, G., 1993, ‘Strategic spillovers in patent races’, *International Journal of Industrial Organization*, 11:139-46.

Delbono, F., and Denicolo, V., 1990, ‘R&D Investment in a Symmetric and Homogeneous Oligopoly: Bertrand vs Cournot’, *International Journal of Industrial Organization*, 8(2):297-313.

Eaton, B.C., and Eswaran, M., 1997, ‘Technology-trading coalitions in supergames’, *RAND Journal of Economics*, 28(1):135-49.

Fölster, S., 1995, ‘Do subsidies to cooperative R&D actually stimulate R&D investment and cooperation?’, *Research Policy*, 24:403-17.

Fransman, M., 1990, *The market and beyond: Cooperation and competition in information technology development in the Japanese System*, Cambridge University Press, Cambridge.

Greenlee, P., 1998, *Endogenous Formation of Competitive Research Sharing Joint Ventures*, Working Paper, U.S. Department of Justice.

Grindley, P., Mowery, D., and Silverman, B., 1994, ‘SEMATECH and collaborative research: lessons for the Design of High Technology Consortia’, *Journal of policy analysis and management*, 35:723-58.

Hinloopen, J., 1994, *Subsidising Cooperative and Non-Cooperative R&D in Duopoly with Spillovers*, European University Institute Working Paper ECO No. 94/25.

Katz, M.L., 1986, ‘An analysis of cooperative research and development’, *RAND Journal of Economics*, 17(4):527-43.

Kamien, M.I., Muller, E., and Zang, I., 1992, ‘Research Joint Ventures and R&D Cartels’, *AER*, 82(5):1293-1306.

Kamien, M.I., and Zang, I., 1993, ‘Competing Research Joint Ventures’, *Journal of Economics and Management Strategy*, 2(1):23-40.

Kamien, M.I., and Zang, I., 1998, *Meet Me Halfway: Research Joint Ventures and Absorptive Capacity*, Mimeo, Department of Managerial Economics and Decision Sciences, J.L. Kellogg Graduate School of Management, Northwester University.

Katsoulacos, Y., and Ulph, D., 1998a, ‘Endogenous Spillovers and the Performance of Research Joint Ventures’, *Journal of Industrial Economics*, 46(3):333-57.

Katsoulacos, Y., and Ulph, D., 1998b, ‘Innovation Spillovers and Technology Policy’, *Annales d’Economie et de Statistique*, 40-50:589-607.

Kesteloot, K., and Veugelers, R., 1995, ‘Stable R&D Cooperation with Spillovers’, *Journal of Economics & Management Strategy*, 4(4):651-72.

Kogut, B., 1989, ‘The Stability of Joint Ventures: Reciprocity and Competitive Rivalry’, *Journal of Industrial Economics*, 38(2):183-98.

Link, A.N., and Bauer, L.L., 1989, *Cooperative Research in U.S. Manufacturing: Assessing Policy Initiatives and Corporate Strategies*, Lexington Books, Lexington, MA.

Link, A., and Tancy, 1989, Lost reference.

Mansfield, E., 1985, ‘How Rapidly does New Industrial Technology Leak Out?’, *Journal of Industrial Economics*, 34:217-23.
Mariti, P., and Smiley, R.H., 1983, ‘Co-operative Agreements and the Organization of Industry’, *Journal of Industrial Economics*, 31(4):437-51.
Peck, M.J., 1986, ‘Joint R&D: The case of Microelectronics and Computer Technology Corporation’, *Research Policy*, 15:219-31.
Pérez-Castrillo, J.D., and Sandonís, J., 1997, ‘Disclosure of know-how in research joint ventures’, *International Journal of Industrial Organization*, 15(1):51-75.
Poyago-Theotoky, J., 1995, ‘Equilibrium and Optimal Size of a Research Joint Venture in an Oligopoly with Spillovers’, *Journal of Industrial Economics*, 43(2):209-25.
Poyago-Theotoky, J., 1999, ‘A Note on Endogenous Spillovers in a Non-Tournament R&D Duopoly’, *Review of Industrial Organization*, 15:253-62.
Rosen, R.J., 1991, ‘Research and Development with Asymmetric Firm Sizes’, *RAND Journal of Economics*, 22:411-29.
Rosenkranz, S., 1998, *To Reveal or Not to Reveal: The Case of Research Joint Ventures with Two-Sided Incomplete Information*, CEPR Discussion Paper No. 1985, Wissensschaftszentrum Berlin.
Salant, S.W., and Shaffer, G., 1998, ‘Optimal Asymmetric Strategies in Research Joint Ventures’, *International Journal of Industrial Organization*, 16(2):195-208.
Shaffer, S., 1995, ‘Stable Cartels with a Cournot Fringe’, *Southern Economic Journal*, 61(3):744-54.
Steurs, G., 1995, ‘Inter-industry R&D spillovers: What difference do they make’, *International Journal of Industrial Organization*, 13:249-76.
Snyder, C., and Vonortas, N., 2000, *Multimarket and Multiproject Contact in Research Joint Ventures*, Paper presented at the *AEA* 2000 Meetings.
Uenhora, M., 1985, ‘Increased reliance of modern industrial technology on scientific outcomes’, in Bartocha, B., and Okamura, S., *Transforming Scientific Ideas into Innovations*, Japan Society for the Promotion of Science, Tokyo.
Veugelers, R., and De Bondt, R., 1992, ‘Cooperative Innovative Activities’, in Antonelli, C. (ed.), *The Economics of Information Networks*, North-Holland, Amsterdam.
Yi, S.S., 1998, *Endogenous formation of joint ventures with efficiency gains*, Working paper, Dartmouth College.
Yi, S.S., and Shin, H., 2000, ‘Endogenous Formation of Research Coalitions’, *International Journal of Industrial Organisation*, 18(2):29-56.