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ENDOGENOUS SPILLOVERS AND THE PERFORMANCE OF RESEARCH JOINT VENTURES*

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We present a model of R&D with endogenous spillovers and demonstrate that noncooperation can produce *maximal* spillovers. The only other noncooperative outcome is minimal spillovers. When noncooperation achieves maximal spillovers so does an RJV, whereas minimal noncooperative spillovers imply partial—but not necessarily maximal—spillovers by an RJV. Partial RJV spillovers are chosen for anti-competitive reasons and an RJV may also close a lab for anti-competitive reasons. The possibility of anti-competitive outcomes is precluded in the existing literature on RJVs which focuses on symmetric outcomes. Our model predicts when anti-competitive behaviour by an RJV arises.

I. INTRODUCTION

OVER the last twenty years a considerable body of empirical work has been undertaken to try to establish the magnitude of R&D spillovers. Despite the conceptual and empirical difficulties involved in estimating these spillovers, a recent survey by Griliches [1995] concluded that 'there has been a significant number of reasonably well done studies all pointing in the same direction: R&D spillovers are present, their magnitude may be quite large and social rates of return remain significantly above private rates.' These spillovers can be both intra-industry and inter-industry though the magnitudes vary across industries.[1] As pointed out by Bernstein and Nadiri [1988] 'the existence of significant intra- and inter-

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[1] In the case of inter-industry spillovers it is important to distinguish between industries as senders or receivers of spillovers—see Bernstein and Nadiri [1988]. There is also some evidence that R&D done by other firms may be either a substitute or complement for a firm's own R&D and that spillovers associated with product innovation may be lower than those for process innovation—see Geroski [1995].

industry spillovers has important implications both with respect to tax effects on R&D investment and for competition policy relating to joint R&D ventures. These issues have yet to be investigated.[1]

Over the last ten years there has been a considerable interest in the role that research joint ventures (RJVs) might play in helping to overcome some of the market failures associated with R&D and innovation.[2] Economists have investigated the extent to which RJVs might allow firms to internalise R&D spillovers, co-ordinate their research activities and achieve higher R&D output while economising on R&D inputs.

However virtually all the existing literature—both theoretical and empirical—treats as *exogenous* the R&D spillover that arises both in the absence of an RJV and once the RJV has formed.[3,4] However, if one wants to fully understand the impact of RJVs on innovative performance, it seems somewhat odd to treat a major component of this—the amount of spillover from one firm to the other—as purely exogenous. After all, if RJVs are thought to be necessary in order to increase the amount of information sharing/research coordination between firms, then we ought to prove that this would be low in the absence of RJVs and high in their presence.[5]

Moreover, since all other aspects of an RJV's innovative performance—the amount of R&D it undertakes, its incentive and ability to eliminate needless duplication—depends crucially on the spillover it achieves, this unsatisfactory treatment of spillovers affects our understanding of every aspects of an RJV's innovative performance.

Accordingly in this paper we wish to develop an analytical framework in which we can examine the effects of RJVs on all aspects of innovative

[2] See, for example, Katz [1986], d'Aspremont and Jacquemin [1988], Katz and Ordover [1990], Kamien, Muller and Zang [1992], Suzumura [1992], Motta [1992a, 1992b], Crepon *et. al.* [1992], Kesteloot and De Bondt [1993], Poyago-Theotoky [1995], Rosenkranz [1996], Beath, Poyago-Theotoky and Ulph [1997].

[3] For example, d'Aspremont and Jacquemin [1988] assume that the same spillover parameter applies in the RJV as in the noncooperative equilibrium. While Motta [1992b], Crepon *et. al.* [1992], Beath, Poyago-Theotoky and Ulph [1997] assume that the RJV can achieve full information sharing/ research design.

[4] Katz [1986] is the only paper we know of in which firms choose spillovers (what he calls 'R&D output sharing') in an RJV. His paper differs from ours in the following respects: spillovers in the non-cooperative equilibrium are fixed; spillovers arise solely from information-sharing and not research-design; the RJV operates a single lab by assumption; he considers only process innovation; firms operate in non-complementary industries; he considers only complementary research discoveries; he confines attention to purely symmetric outcomes.

[5] An important qualification that has to be made to the remarks in this paragraph is that the literature has recognised the possibility that a firm's capacity to benefit from R&D done by other firms may depend on the amount it itself is spending on R&D. In a sense then, the *recipient* of a spillover may be able to affect the degree of spillover it receives through actions it takes. In this case we would have endogenous spillovers. The crucial point is that the maximum amount which the recipient can receive is still limited by what the sender sends. The whole point of this paper is to endogenise the spillover chosen by the sender.

performance in the case where R&D spillovers are *endogenously* chosen both in the absence of an RJV and once the RJV has formed.

When spillovers are treated as endogenous, it becomes necessary to take account of a number of distinctions, some but not all of which have been recognised in the existing literature. This generates a very rich modelling framework, so, for simplicity, we confine attention here to the case where there are just two firms contemplating entry into an RJV.

The distinctions that need to be made are as follows.

Firstly we have to clarify the source and nature of spillovers. The amount of spillover from one firm to the other actually depends on two factors:[6] the *adaptability* of the research to the other firm (the other firm's *capacity* to utilise the research) and the amount of *information sharing*. The former has to be chosen before the research is carried out—i.e. at the *research design* stage—while the latter can be decided after any discovery is made.

Secondly we have to say something about the nature of product market competition, since this will clearly have a bearing on the incentives of a firm to give a spillover which benefits the other firm but may, or may not, harm itself. In particular, it would seem useful to distinguish between the following two cases—amongst others:

(a) Firms are in the *same* industry. In this case any spillover from one firm to the other will make the firm receiving the spillover more competitive, so increasing its profits, but will lower the profits of the firm giving the spillover.
(b) Firms are in *different but complementary* industries. Here a spillover from one firm to the other enables the receiving firm to improve its product or technology enabling it to attract more consumers and increase its profits. In this case, however this has a beneficial impact on the profits of the firm giving the spillover.

This previous consideration bears on the incentives of firms to share information or to coordinate their research design when they act independently outside an RJV. When they act cooperatively inside an RJV, then incentives to make their research adaptable or to share information depend on the nature of the *joint* profit function. In particular it turns out to be important to say something about the case where one firm has made more progress than another and about how industry profits vary as we increase the progress of the firm that is behind. While many factors bear on this, one relates to our third distinction which is that between *product* and *process* innovation. To see this, consider the case where one firm is very far ahead of the other. In the case of *product*

[6] The idea that the amount of spillover depends on both research design and information sharing is also made by Beath, Poyago-Theotoky and Ulph [1997].

innovation, the leading firm may have to cut its price a lot to prevent the firm that is behind from taking too much of the market. An increase in the quality of the product made by the firm that is behind can allow both firms to raise their prices and hence *increase* joint profits. This contrasts with the case of *process innovation*, where, when the gap is very wide, the leading firm may be able to price the other firm out of the market and make monopoly profits and so an increase in the progress made by the firm that is behind will *lower* joint profits.

Fourthly we have to specify the degree of *technical*[7] *substitutability* or *complementarity* between the research discoveries made by one firm and those achieved by the other. For illustrative purposes consider just two extreme possibilities amongst many others.

- In the *pure substitute* case firms essentially make the same discovery—i.e. they are duplicating each other's research. This implies that if *both* firms discover then neither can benefit from any spillover from its rival. Clearly in this case there is scope for an RJV to undertake R&D more efficiently by eliminating this needless duplication.
- When research discoveries are *pure complements* then firms will make discoveries which directly carry forward the work that the other has done. So, to the extent that it is shared, the progress made by one firm just adds to the progress made by the other. It should be noted that virtually all the literature on RJVs assumes that spillovers take this additive form.

In this paper we take the degree of substitutability and complementarity of research discoveries to be exogenous.

Finally, as pointed out above, it is important to distinguish between *cooperation and information sharing/research design coordination*. We assume that when firms join an RJV and so organise all aspects of innovation *cooperatively*, they act so as to maximise expected joint profits.[8] However, just because firms choose to cooperate it cannot be automatically assumed that they will choose to share all information and coordinate research design. Indeed we will show that there are cases where neither of these happen inside an RJV.[9] Equally, the fact that firms choose

[7] We stress this to distinguish our concept from the familiar idea of **strategic** substitutes and complements.

[8] This assumes that firms are fully able to implement any agreement they reach concerning information sharing etc. In this paper we just want to understand how *in principle* RJVs might operate when spillovers are endogenous. There is important further work to be done on the implementability of the agreements explored in this paper and hence on the genuine effects of RJVs on innovative performance.

[9] This contrasts with the findings by Katz [1986] where he shows that, in the context of his more special model, an industry-wide RJV always achieves full information-sharing.

not to cooperate does not automatically mean that they will neither coordinate research design nor share information. Again we will give examples where full coordination and information sharing can happen outside an RJV.

In what follows we will show that all these factors and distinctions matter when comparing the performance of RJVs to the outcomes of non-cooperative R&D competition. We develop a very general model of R&D between two firms which incorporates all the factors set out above. We then show how the results obtained in both the cooperative and the non-cooperative equilibrium depend on the features we have highlighted.

An important finding of this paper is that there are a number of respects in which RJVs may sometimes act in an anti-competitive fashion. This arises when the RJV deliberately generates asymmetric outcomes in terms of information sharing or R&D inputs. The possibility of anti-competitive outcomes is precluded in the existing literature which focuses on symmetric outcomes.

More specifically, the main conclusions we reach are the following.

Cooperative vs Non-Cooperative Information Sharing

(i) Under one set of circumstances it is possible that the non-cooperative equilibrium may achieve maximal information-sharing. In all other circumstances the non-cooperative equilibrium produces minimal information-sharing.

(ii) In the situation which would give rise to minimal information-sharing in the non-cooperative equilibrium, then in an RJV:
   (a) when both forms discover it will always be the case that at least one firm maximally shares information;
   (b) when only one firm discovers it may choose minimal, maximal or partial information sharing.

(iii) Whenever firms in an RJV decide not to fully share information, they do this in order to prevent the market from becoming too competitive—i.e. for anti-competitive reasons.

(iv) The situation which leads to maximal information-sharing outcome in the non-cooperative equilibrium produces maximal information-sharing within the RJV.

Cooperative vs Non-Cooperative R&D Cost Sharing

(i) In the non-cooperative equilibrium firms undertake an equal amount of R&D.

(ii) Cost saving is one of the factors lying behind the RJVs decision as to whether to operate one or two labs and can certainly lead the RJV to reap efficiency gains in carrying out R&D through eliminating needless duplication of effort.

(iii) However eliminating needless duplication is not the only element of the cost calculation—diminishing returns are an important cost reason for having two labs.
(iv) Cost considerations tend to be the dominant factor when (a) research outputs are very close substitutes; (b) firms are willing to share a lot of information.
(v) The RJV may also close a lab for anti-competitive reasons—to prevent its having to face a very competitive situation when both firms discover.
(vi) The RJV may wish to keep both labs open in order to exploit very strong complementarities between the research output of the two firms.

The plan of this paper is as follows. In the next section we set out the formal model. In Section III we examine the non-cooperative equilibrium, and in Section IV the cooperative equilibrium. Section V concludes.

II. THE MODEL

There are two firms. Each firm is engaged in research which, through a combination of any discovery it makes itself and any spillover it receives from its rival, enables it to make a certain quantum of progress, $q \geq 0$, in either product improvement or cost reduction. If a firm makes a discovery then, in the absence of any spillover from the other firm, the progress it makes is set at 1.

The firm's research decisions are taken in three stages.

First, each firm faces a range of research projects it can undertake. Each project enables it to make the same unit progress if it succeeds in making a discovery. However, projects differ in the capacity, κ, of the other firm to adapt the discovery to its own use. We assume that κ, can take any value in the interval $[\underline{\kappa}, \overline{\kappa}]$ $0 \leq \underline{\kappa} < \overline{\kappa} \leq 1$. Consequently, in Stage 1, before undertaking any R&D, the firm has first to choose the particular line of research to pursue—the *research design*—and hence the value of κ.

Then, in Stage 2, firms have to choose the amount of R&D that each will do. The amount of R&D undertaken by a firm determines the probability that it will make a discovery along its chosen line of research. A given amount of R&D expenditure produces the same probability of discovery whatever line of research is chosen. So there are no cost reasons for choosing one line of research rather than another and the choice of research design is purely strategic. The R&D technology faced by each firm is described by the R&D cost function, $c(p)$, which determines the total R&D expenditure required to produce a probability p, $0 \leq p \leq 1$, of discovery. We assume that $c(.)$ satisfies the following conditions:

$$c(0) = 0; \quad c'(0) = 0; \quad c''(p) > 0; \quad \lim_{p \to 1} c(p) = \lim_{p \to 1} c'(p) = \infty.$$

Most of these conditions are self-explanatory and ensure that, as long as a firm has a positive marginal benefit from undertaking R&D, it will also have a positive probability of innovating, while no firm can end up innovating for sure.

Finally, in Stage 3, if a firm succeeds in making its discovery, it can choose the fraction, σ, of the information it wishes to share with the other firm. We assume that σ can be chosen to take any value in the interval $[\underline{\sigma}, \overline{\sigma}]$ $0 \leq \underline{\sigma} < \overline{\sigma} \leq 1$.

Notice that we allow for the possibility of involuntary information leakages when $\underline{\sigma} > 0$. The magnitude of this involuntary spillover will depend on a number of factors such as technology (especially the technology for industrial espionage) and the degree of protection of intellectual property rights—the greater the protection of intellectual property, the smaller is $\underline{\sigma}$. An economy in which there was no patent protection (and no other form of protection) would correspond to having $\underline{\sigma} = 1$, while perfect patent protection would correspond to having $\underline{\sigma} = 0$.

The firm can base the decision about the amount of information to share on whether *both* firms have succeeded in making the discovery, or whether it alone is the sole *winner* of the race to innovate. Let σ^b and σ^w denote, respectively, the values of the *information sharing* parameter chosen in each of these two circumstances.

The total spillover given by a firm that has made a discovery is exactly $\delta = \kappa.\sigma$. Given our assumptions $\underline{\delta} \leq \delta \leq \overline{\delta}$, $0 \leq \underline{\kappa}.\underline{\sigma} = \underline{\delta} < \overline{\delta} = \overline{\kappa}.\overline{\sigma} \leq 1$. Obviously a firm which has failed to make a discovery has no information to share and can give no spillover to the other firm.

A firm's research strategy is described by the four variables $(\kappa, p, \sigma^b, \sigma^w)$.

The total quantum of progress, q, which a firm makes depends on the amount of progress it makes as a result of its own discovery—which we refer to as *self* progress, and denote by s—and on the amount it gains from anything it learns from the other firm—which we refer to as *received* progress and denote by r. Notice that s takes just the two values: 0, if the firm does not make a discovery, and 1 if it does. If the other firm fails to make a discovery then $r = 0$, whereas if the other firm makes a discovery then $r = \delta$, where δ is the spillover the firm receives from the other firm.

The relationship between q, r and s will depend on the degree of substitutability or complementarity between the research discoveries made by the two firms. We represent this through the function $q = \tau(s, r)$. For much of the paper this can be taken to be quite a general function which is non-decreasing in both arguments. For illustrative purposes, however, it will help to have in mind the special case where

$$(1) \qquad \tau(s,r) \equiv \begin{cases} s+r, & \gamma = \infty \\ \left[s^{\frac{1+\gamma}{\gamma}} + r^{\frac{1+\gamma}{\gamma}}\right]^{\frac{\gamma}{1+\gamma}}, & 0 < \gamma < \infty \\ MAX[s,r], & \gamma = 0 \end{cases}$$

and γ is a parameter reflecting the degree of complementarity between the research discoveries.[10]

To get the intuition, it may help to consider the two extreme cases.

The first is where research discoveries are **perfect complements**. This is the case where $\gamma = \infty$ and so the function $\tau(.)$ takes the form $q = s + r$. Thus the research made by each firm fully takes forward the research by the other—which is what we would want to say when the discoveries are perfect complements. This is the case which is typically assumed in the literature.

The second case is the where research discoveries are **perfect substitutes**. This is the case where $\gamma = 0$ and the function $\tau(.)$ takes the form $q = MAX[s, r]$. In this case each firm is essentially duplicating the other's research and so the total progress that can be made is just the maximum amount that is either made or received. This again captures precisely what we would have in mind happening when firms are pursuing exactly the same line of research.

In this paper the degree of complementarity between research discoveries—i.e. the parameter γ—will be taken as exogenous, though, as we shall see, the precise value of this parameter affects the results.

Notice that an important property of the function $\tau(.)$ is that

$$(2) \qquad \tau(s, 0) \equiv s; \quad \tau(0, r) \equiv r$$

so that the total progress that a firm makes is limited to self progress when it receives nothing from the other firm, while it is limited to the received progress in the case where it makes no progress itself. This is independent of the degree of complementarity, so, as we would expect, the degree of complementarity or substitutability between research discoveries only matters in the case where both firms have discovered.

Finally, in order to understand the incentives to make research adaptable or to share information, we need to examine how profits depend on the amount of progress made by each of the two firms.

Let $\pi(q, \tilde{q})$ denote the operating profits of a firm which has made progress q, while the other firm has made progress $\tilde{q} \geq 0$.

We assume that each firm always benefits from any progress which it itself makes, so

[10] It is straightforward to show that the expression for $\tau(.)$ given for the intermediate values of γ tends asymptotically to the other two expressions as γ tends to each of its two limiting values.

$$(3) \qquad \frac{\partial \pi}{\partial q} > 0.$$

How a firm's profits respond to progress made by the other firm depends on the nature of the product markets in which they are operating. In the analysis that follows we distinguish just two cases.[11]

Case A Each firm's profits are reduced by progress made by the other, i.e.

$$(4) \qquad \frac{\partial \pi}{\partial \tilde{q}} < 0.$$

This is the assumption that we would typically make if firms were in the **same industry**—though obviously it can apply more widely.

However, in this case we would also want to assume that the negative effect of progress by the rival is outweighed by the beneficial effects of a firm's own progress. More precisely, when both firms have made the same amount of progress, then further equal progress by each increases profits, i.e.

$$(5) \qquad \frac{d\pi(q, q)}{dq} > 0.$$

Case B Each firm's profits are increased by progress made by the other, i.e.

$$(6) \qquad \frac{\partial \pi}{\partial \tilde{q}} > 0.$$ [12]

This assumption would apply when firms were operating in **different but complementary industries**.

When firms are in an RJV they act cooperatively to maximise joint profits. So let $\Pi(q, \tilde{q}) \equiv \pi(q, \tilde{q}) + \pi(\tilde{q}, q)$ denote joint profits when one firm (it does not matter which) has made progress $q \geq 0$, while the other has made progress $\tilde{q} \geq 0$. In order to understand the incentives to share information inside an RJV, it is important to consider the case where one firm—the leader—has made more progress than the other—the follower—and to consider what happens to joint profits as we increase the progress of the follower.

[11] Clearly there is a third case where firms are in completely independent industries, so a spillover from one firm to the other increases the profits of the firm receiving the spillover but has no effect on the profits of the firm giving the spillover. The analysis of this case is very similar to the complementary industry case, except that in the non-cooperative equilibrium firms are indifferent as to the amount of information they reveal. For expositional purposes we have confined our attention to the two cases mentioned in the text.

[12] Notice that (6) and (3) imply (5).

So assume now that $q > 0$, and that $0 \leq \tilde{q} < q$. We want to know how $\Pi(.)$ varies with $\tilde{q}$.

In **Case B** this is straightforward—$\Pi(.)$ is a *strictly increasing* function of $\tilde{q}$.

In **Case A** however, virtually anything can happen. There are four sub-cases:

A.1 $\Pi(.)$ is a *strictly increasing* function of $\tilde{q}$.
A.2 $\Pi(.)$ is a *strictly decreasing* function of $\tilde{q}$.
A.3 $\Pi(.)$ is an *essentially convex* function of $\tilde{q}$—i.e. it initially falls and then rises before $q = \tilde{q}$.
A.4 $\Pi(.)$ is an *essentially concave* function of $\tilde{q}$—i.e. it initially rises and then falls before $q = \tilde{q}$.

As discussed in Beath, Katsoulacos and Ulph [1995], **Case A.3** can arise when firms are in the same industry, there is Cournot competition and *process innovation*, whereas **Case A.4** can arise when firms are in the same industry producing vertically differentiated products—i.e. there is *product innovation* - and Bertrand competition.[13]

This completes the description of the model, and we now take up in turn the analysis of the noncooperative and then the cooperative equilibrium.

III. THE NON-COOPERATIVE EQUILIBRIUM

This takes the form of a 3-stage game. In the final stage—Stage 3—firms choose how much information to reveal conditional on whether they are the sole innovator, or on whether both firms have discovered. In Stage 2 they choose their R&D and hence their probability of success. In Stage 1 they choose their research design—the adaptability parameter. We analyse these stages in turn.

III(i). *Stage 3*

Given our assumptions, Stage 3 is straightforward. We have:

Theorem 1

If $\kappa_1 > 0$, $\kappa_2 > 0$, $\gamma > 0$, then:

(i) in **Case A** $\sigma_1^b = \sigma_2^b = \sigma_1^w = \sigma_2^w = \underline{\sigma}$;
(ii) in **Case B** $\sigma_1^b = \sigma_2^b = \sigma_1^w = \sigma_2^w = \overline{\sigma}$.

Proof: Obvious.

[13] See Beath, Katsoulacos and Ulph [1987] for a detailed analysis of this latter case.

It only remains to dispose of the cases not explicitly covered by this theorem.

(i) If, at Stage 1, Firm i has chosen $\kappa_i = 0$ then its spillover will be zero whatever amount of information-sharing it chooses. In this case there is no loss in simply assigning the equilibrium values of the information-sharing variables that are given by Theorem 1.

(ii) Suppose $\gamma = 0$. When only one firm discovers then, since the amount of progress each firm makes is independent of γ, the equilibrium levels of the information-sharing variables that are chosen are necessarily the same as given by Theorem 1. If both firms discover, then, since $\gamma = 0$, the amount of progress each firm makes is completely unaffected by any information that is shared. So, once again, there is no loss of generality in simply assigning the equilibrium values of the information-sharing variables given by Theorem 1 in this case.

Thus the conclusions of Theorem 1 can be extended to all cases. Consequently we have:

Corollary 1

In all cases the equilibrium information-sharing variables are symmetric for the two firms and are the same whether one firm has discovered or whether both have discovered. If we denote the common equilibrium information-sharing parameter by σ^e, then in **Case A** $\sigma^e = \underline{\sigma}$, and $\sigma^e = \overline{\sigma}$ in **Case B**.

The interesting point about the main result in this section is that, in **Case B**, firms may choose to maximally reveal information even in the absence of cooperation.

This completes the analysis of Stage 3.

III(ii). *Stage 2*

Notice that the equilibrium information-sharing variables, σ^e, chosen at Stage 3 do not depend on anything chosen at Stage 2 and so can be taken as given at his Stage.

By assumption, the analysis of this Stage also takes as given the values of adaptability variables chosen by the two firms at Stage 1. Let κ_i be the value chosen by Firm i .

Knowing these two dimensions of each firm's spillovers, we can work out the amount of progress made by each of the two firms—i.e. the magnitudes of the variables q and $\tilde{q}$ that are arguments of each firm's profit function $\pi(q, \tilde{q})$. Consequently we can define the following profit levels:

For $i = 1, 2$, and for $j = 1, 2; j \neq i$, let

$\pi_i^b \equiv \pi[\tau(1, \kappa_j.\sigma^e), (1, \kappa_i.\sigma^e)]$ be the operating profits of Firm i if both firms discover;
$\pi_i^w \equiv \pi(1, \kappa_i.\sigma^e)$ be the operating profits of Firm i if it alone discovers;
$\pi_i^\ell \equiv \pi(\kappa_j.\sigma^e, 1)$ be the operating profits of Firm i if Firm j alone discovers;
$\pi^0 \equiv \pi(0, 0)$ be the profits of each firm if neither firm discovers.

Using these, we can now define the following terms which play a key role in the analysis of the R&D equilibrium.

$\alpha_i \equiv \pi_i^b - \pi_i^\ell$ is the *competitive threat*[14] facing Firm i: the difference between the profits of firm i if it innovates and those it makes if it fails to innovate conditional on the firm j's having innovated;

$\beta_i \equiv \pi_i^w - \pi^0$ is the *profit incentive* facing Firm i: the difference between the profits firm i makes if it innovates and those it makes if it fails to innovate conditional on the firm j's not having innovated.

In order to explore what can be said about the sign of each firm's *competitive threat*, notice that it is always the case that:

(i) given (1), $\tau(1, \kappa_i.\sigma^e) \geq 1$;
(ii) given (3), $\pi_i^\ell \leq \pi(1, 1)$.

Consider first the symmetric case where $\kappa_1 = \kappa_2 = \kappa$, say. Here it follows from (5)—which, remember, holds in both **Case A** and **Case B**—that

$$\pi_i^b = \pi[\tau(1, \kappa.\sigma^e), \tau(1, \kappa.\sigma^e)] \geq \pi(1, 1),$$

and consequently both *competitive threats* are non-negative.

Now suppose $\kappa_2 > \kappa_1$, then $\tau(1, \kappa_2.\sigma^e) \geq \tau(1, \kappa_1.\sigma^e)$ and so

$$\pi_1^b = \pi[\tau(1, \kappa_2.\sigma^e), \tau(1, \kappa_1.\sigma^e)] \geq \pi[\tau(1, \kappa_1.\sigma^e), \tau(1, \kappa_1.\sigma^e)] \geq \pi(1, 1),$$

where the first inequality follows from (3) and the second from (5). Consequently Firm 1's competitive threat is certainly non-negative.

On the other hand, each firm's *profit incentive* is strictly positive. To see this, notice that in **Case A** $\pi_i^w = \pi(1, \kappa_i.\sigma^e) \geq \pi(1, 1) > \pi(0, 0) = \pi^0$, where the last inequality comes from (5). On the other hand, in **Case B** $\pi_i^w = \pi(1, \kappa_i.\sigma^e) \geq \pi(1, 0) > \pi(0, 0)$, where the last inequality comes from (3). Therefore in all the cases considered here we have $\beta_i > 0$.

Using the above definitions, we can see that in Stage 2 Firm 1 has the following level of expected profits:

$$p_1 p_2 \pi_1^b + p_1(1 - p_2)\pi_1^w + (1 - p_1)p_2\pi_1^\ell + (1 - p_1)(1 - p_2)\pi^0 - c(p_1). \tag{7}$$

[14] This terminology comes from Beath, Katsoulacos and Ulph [1995] to which the reader is referred for a more extensive analysis of the role of competitive threats and profit incentives in R&D competition.

There is an analogous expression for Firm 2.

We are looking for a Nash equilibrium in which each firm chooses its probability of discovery—and hence its level of R&D—in order to maximise expected profits, taking as given the probability of discovery—and hence the level of R&D—chosen by the other firm.

The first order condition (f.o.c.) for profit-maximisation for firm i is

$$p_j\alpha_i + (1 - p_j)\beta_i \leq c'(p_i), \quad p_i \geq 0, \tag{8}$$

where the inequalities hold with complementary slackness.

In order to determine the Nash equilibrium, it is useful to first characterise firm i's reaction function as implicitly defined by (8).

Since the LHS of (8) is finite for all $p_j \in [0, 1]$, it follows from our assumptions on the R&D cost function that neither firm will ever choose to innovate for sure—i.e. $p_i <, i = 1, 2$.

It follows that if $\alpha_i \geq 0$ then for all $p_j \in [0, 1]$ the LHS of (8) is strictly positive, and so, given the assumptions on the R&D cost function, we must have $p_i > 0$ and

$$p_j.\alpha_i + (1 - p_j)\beta_i = c'(p_i). \tag{9}$$

Equation (9) implicitly defines firm i's reaction function. It is easy to see that p_i will be a *strictly increasing* function of p_j if $\alpha_i > \beta_i$ and a *strictly decreasing* function of p_j if $\alpha_i < \beta_i$.

If $\alpha_i < 0$ then, for $p_j \in \left[0, \frac{\beta_i}{\beta_i - \alpha_i}\right)$ the LHS of (8) is positive and so $p_i > 0$ and p_i is a strictly decreasing function of p_j. On the other hand, for $p_j \in \left[\frac{\beta_i}{\beta_i - \alpha_i}, 1\right]$ the LHS of (8) is non-positive and so $p_i = 0$.

Putting all this together we now have:

Theorem 2

There is a unique Stage 2 equilibrium (p_1^e, p_2^e) in which

(i) $p_i^e < 1, \quad i = 1, 2$;
(ii) $p_i^e > 0 \quad \text{if} \quad \alpha_i \geq 0$;
(iii) for at least one firm $p_i^e > 0$.

It is important to notice that these equilibrium probabilities depend on the *competitive threats* and *profit incentives* facing each of the two firms and are hence functions of the adaptability variables κ_1 and κ_2 chosen at Stage 1.

Corollary 2

In the symmetric case in which $\kappa_1 = \kappa_2$ and so $\alpha_1 = \alpha_2 = \alpha \geq 0$; $\beta_1 = \beta_2 = \beta > 0$ then the unique equilibrium is the symmetric one in which each firm chooses an equilibrium probability p^e, $0 < p^e < 1$, which satisfies the equation

$$p^e\alpha + (1 - p^e)\beta = c'(p^e).$$

This completes the analysis of Stage 2.

III(iii). *Stage 1*

If we substitute the equilibrium values of the R&D probabilities back into the expression for expected profits of Firm 1 given by equation (7), then the expected present value of profits facing Firm 1 at Stage 1 will be a function of the adaptability variables κ_1 and κ_2. Denote this by $V^1(\kappa_1.\kappa_2)$. By analogy we can derive the expected present value of profits of Firm 2 at this Stage: $V^2(\kappa_1.\kappa_2)$.

In Stage 1 Firm 1 will choose κ_1 to maximise $V^1(.)$ taking κ_2 as given. We have:

$$\text{(10)} \qquad \frac{\partial V^1}{\partial \kappa_1} = \sigma^e\left\{p_1 p_2 \frac{\partial \pi_1^b}{\partial \bar{q}} \cdot \frac{\partial \tau(1, \kappa_1.\sigma^e)}{\partial r} + p_1(1 - p_2)\frac{\partial \pi_1^w}{\partial \bar{q}}\right\} + \theta \frac{\partial p_2}{\partial \kappa_1}$$

where

$$\theta = p_1[\pi_1^b - \pi_1^w] + (1 - p_1)[\pi_1^\ell - \pi^0].$$

The first term on the RHS of (10) is the *direct effect* of an increase in κ_1 and reflects the benefit Firm 1 will get by giving greater spillovers to Firm 2 when it (Firm 1) has made a discovery.

The second term on the RHS of (10) is the *indirect effect* of an increase in κ_1 and reflects the impact on Firm 1's profits from any induced change in Firm 2's probability of success.

To see what can be said about this let us take the two effects in turn.

Direct effect

Notice first of all that $\frac{\partial \tau(1, \kappa_1.\sigma^e)}{\partial r} \geq 0$ and is zero only when research outputs are perfect substitutes.

In **Case A** $\frac{\partial \pi_1^b}{\partial \bar{q}} < 0, \frac{\partial \pi_1^w}{\partial \bar{q}} < 0$ and $\sigma^e = \underline{\sigma}$, so the direct effect is zero if there are no involuntary information leakages (i.e. if $\underline{\sigma} = 0$) and negative otherwise.

In **Case B** and $\frac{\partial \pi_1^b}{\partial \bar{q}} > 0, \frac{\partial \pi_1^w}{\partial \bar{q}} > 0$ and $\sigma^e = \bar{\sigma} > 0$, so the direct effect is unambiguously positive.

Indirect effect

This depends on the signs of θ and of $\frac{\partial p_2}{\partial \kappa_1}$.

It is easy to see from the definitions that in **Case A** θ can be positive or negative, whereas in **Case B** it is unambiguously positive.

Turning to the effects of an increase in κ_1 on p_2 notice first of all that this operates via the impact of κ_1 on the competitive threats and profit incentives of the two firms and that these are all proportional to σ^e. So, in **Case A** if there are no involuntary leakages this effect will also be zero.

Consider then what can be said for the case where $\sigma^e > 0$. There are two effects.

- An increase in κ_1 will reduce both the *competitive threat* and the *profit incentive* facing Firm 1, and so will unambiguously shift its R&D reaction function. The effect of this on p_2 will depend on whether Firm 2's reaction function is upward or downward sloping—and hence on the relative magnitudes of Firm 2's *profit incentive* and *competitive threat*.
- An increase in κ_1 will increase both π_2^b and π_2^ℓ. The net effect of this on Firm 2's *competitive threat* is ambiguous, so, at this level of generality we cannot say how this affects p_2.

We see then that the overall effect of an increase in κ_1 on p_2 can be positive or negative.

In general, all we can say about the outcome of this stage is the following:

Theorem 3

(i) In **Case A**, if there is no involuntary information sharing (i.e. if $\underline{\sigma} = 0$), then firms are indifferent as to the level of adaptability they choose.

(ii) In all other cases, if the *direct effect* dominates the *indirect effect* then:

(a) in **Case A** $\kappa_1^e = \kappa_2^e = \underline{\kappa}$;

(b) in **Case B** $\kappa_1^e = \kappa_2^e = \overline{\kappa}$.

Thus, if the *direct effect* dominates the *indirect effect*, then *both* dimensions of the spillover take their minimal value in **Case A** and their maximal value in **Case B**. In particular this means that maximal spillovers **can** arise in the absence of cooperation. However it is important to realise also that even though information-sharing takes its maximal value in **Case B**, there is no guarantee that adaptability will be at its maximum.

IV. THE COOPERATIVE EQUILIBRIUM

We assume that when firms operate inside an RJV they will choose the eight variables $(\kappa_1, \kappa_2, \sigma_1^b, \sigma_2^b, \sigma_1^w, \sigma_2^w, p_1, p_2)$ so as to maximise expected joint profits.

Before exploring the details of the solution, notice the following two points.

(I) In any type of outcome ($t = b, w$) of the discovery process the only things that affect industry profits are the combined spillover parameters $\delta_i^t = \kappa_i.\sigma_i^t$. It will simplify our analysis if, from now on, we assume that $\underline{\sigma} = 0, \bar{\kappa} = 1$. On this case we have $\underline{\delta} = 0$; $\bar{\delta} = \bar{\sigma}$ and any possible outcome can be achieved by setting $\kappa_1 = \kappa_2 = 1$ and choosing the appropriate values of information-sharing parameters in the interval $[0, \bar{\sigma}]$. Accordingly we now set $\kappa_1 = \kappa_2 = 1$ and think of the RJV choosing the six variables $(\sigma_1^b, \sigma_2^b, \sigma_1^w, \sigma_2^w, p_1, p_2)$ so as to maximise expected joint profits.

(II) Although these 6 variables are chosen *simultaneously* so as to maximise expected joint profits, in fact the problem has a recursive structure; for any given outcome ($t = b, w$) choose the relevant information-sharing variables so as to maximise joint profits in that particular outcome; then choose the probabilities of discovery (and hence the R&D levels) of the two firms so as to maximise expected joint profits. In what follows we will set out the solution in this recursive structure.

IV(i). *Choice of Information-Sharing Variables When Both Firms Discover*

Joint profits in this case are $\Pi[\tau(1, \sigma_2^b), \tau(1, \sigma_1^b)]$.

In the case where $\gamma = 0$ joint profits are $\Pi(1, 1)$ whatever values of the information-sharing variables are chosen and there is nothing more to be said.

So consider now the case where $\gamma > 0$.

In **Case B** joint profits are strictly increasing in both information-sharing variables and hence the solution is $\sigma_1^b = \sigma_2^b = \bar{\sigma}$.

In **Case A** the situation is more interesting. Notice first of all that when $\gamma > 0$ then $\tau(1, 0) = 1$, but $\tau(1, \bar{\sigma}) > 1$ and so, given (5), the outcome $(\bar{\sigma}, \bar{\sigma})$ in which both firms maximally share information dominates the non-cooperative outcome $(0, 0)$ in which neither firm shares information.

The question is whether the RJV can do better still by having one firm—say Firm 2—fully sharing information, while the other partially shares information. In other words we need to consider whether

$$\Pi[\tau(1, \bar{\sigma}), \tau(1, \sigma_1^b)] > \Pi[\tau(1, \bar{\sigma}), \tau(1, \bar{\sigma})] \text{ for some } \sigma_1^b \in [0, \bar{\sigma}].$$

There are two effects at work. Obviously, having Firm 1 sharing its discovery with Firm 2 increases the profits of Firm 2 and, other things being equal, this increases joint profits. But other things are not equal, because having Firm 2 share in Firm 1's discovery intensifies competition and this damages Firm 1's profits, and hence joint profits. In general it is not clear which of these effects dominates.

Note that if the latter effect dominates then firms will not fully share information in an RJV for anti-competitive reasons, that is in order to avoid the intensification of competition that results from full information-sharing.

Formally the outcome depends on the nature of the joint profit function and in particular, on how joint profits vary with the progress, $\tilde{q}$, made by Firm 2 when Firm 1 has made progress $q = \tau(1, \overline{\sigma}) > 1$ and $\tilde{q}$ varies in the interval $[1, \tau(1, \overline{\sigma})]$—so that $\tilde{q} \leq q$.

As indicated in Section 2 there are 4 separate sub-cases to consider under **Case A**: **Case A.1**–**Case A.4**. But which of these is going to apply will depend in turn on a whole variety of factors:

- whether firms are producing identical or differentiated products;
- if differentiated, whether products are horizontally or vertically differentiated;
- whether we have product or process innovation;
- the degree of substitutability or complementarity between research discoveries—i.e. the precise value of γ;
- the value of $\overline{\sigma}$.

Drawing this discussion together, we can therefore summarise the results of this subsection in:

Theorem 4

When both firms discover then:

(i) when $\gamma = 0$, firms are indifferent as to how much information they share;

(ii) when $\gamma > 0$ then the cooperative values of the information-sharing parameters when both firms discover are as follows:

Case A.1: $(\overline{\sigma}, \overline{\sigma})$;
Case A.2: $(0, \overline{\sigma})$
Case A.3: $(\overline{\sigma}, \overline{\sigma})$ if $\Pi[\tau(1, \overline{\sigma}), \tau(1, \overline{\sigma})] > \Pi[\tau(1, \overline{\sigma})1]$; $(0, \overline{\sigma})$ if $\Pi[\tau(1, \overline{\sigma}), \tau(1, \overline{\sigma})] < \Pi[\tau(1, \overline{\sigma})1]$;
Case A.4: $(\sigma_1^b, \overline{\sigma})$ with $0 < \sigma_1^b < \overline{\sigma}$
Case B: $(\overline{\sigma}, \overline{\sigma})$.

Proof: Follows immediately from the definitions of the various cases.

It is useful to compare this result with the outcome in the non-cooperative equilibrium as given in Theorem 1. In particular, we see that in **Case A** the RJV definitely generates more information-sharing than in the non-cooperative equilibrium though there is no guarantee that it leads to full information-sharing. However in **Case B,** the RJV does not improve on the information-sharing outcomes in the non-cooperative equilibrium. We summarise this in:

Corollary 4

When both firms discover then:

(i) In **Case A** it will always be the case that in an RJV at least one firm maximally shares information, in contrast with the non-cooperative equilibrium where both firms minimally share information.

(ii) Whenever in **Case A** the RJV decides that the second firm will not maximally share information, this is done in order to prevent the market from becoming too competitive—i.e. for anti-competitive reasons.

(iii) In **Case B** the information-sharing outcome is the same as in the non-cooperative equilibrium.

IV(ii). *Choice of Information-Sharing Variables when Only One Firm Discovers*

Given the symmetry of the two firms it does not matter which firm has discovered. Thus the RJV will always set $\sigma_1^w = \sigma_2^w = \sigma^w$, say. We have to determine the value of σ^w.

Joint profits are $\Pi(1, \sigma^w)$. Notice that, since only one firm has discovered, the degree of substitutability/complementarity between research discoveries is irrelevant.

Thus the situation is once again one in which one firm has made progress $q = 1$, while the other has made progress $\tilde{q} = \sigma^w$, so that $0 \leq \tilde{q} \leq \overline{\sigma} \leq 1 = q$. Given the discussion in the previous section we can immediately conclude:

Theorem 5

When only one firm discovers, then the equilibrium value of the information-sharing variable is as follows:

Case A.1:[15] $\sigma^w = \overline{\sigma}$;
Case A.2: $\sigma^w = 0$;
Case A.3: $\sigma^w = \overline{\sigma}$ if $\Pi[1, \overline{\sigma}] > \Pi(1, 0)$, $\sigma^w = 0$ if $\Pi(1, 0) > \Pi[1, \overline{\sigma}]$;
Case A.4: $0 < \sigma^w < \overline{\sigma}$
Case B: $\sigma^w = \overline{\sigma}$.

Proof: Follows immediately from the definitions of the various cases.

[15] It is important to stress that since the value of q and the range of values over which $\tilde{q}$ can range are different in this sub-section from those that prevailed in sub-section IV(i), the fact that the profit function satisfied the conditions for, say, **Case A.1** in sub-section IV(i) does NOT imply that it satisfies the conditions for **Case A.1** in this subsection.

Once again we can contrast the results with those that were obtained in the non-cooperative equilibrium.

Corollary 5
When only one firm discovers then:

(i) whereas, in **Case A**, firms would engage in minimal information sharing in the non-cooperative equilibrium, when they enter an RJV they may choose minimal, maximal or partial information sharing;
(ii) non-maximal information-sharing is again done for anti-competitive reasons—note, however, that in the case of partial information-sharing, while the RJV is acting anti-competitively relative to the social optimum of full information-sharing, it will still be acting more competitively than under non-cooperation;
(iii) the outcome under **Case B** is identical to that in the non-cooperative equilibrium.

While the RJV **may** lead to more information-sharing than is obtained under non-cooperation, this is not guaranteed.

IV(iii). *Choice of Equilibrium Discovery Probabilities*

Define the following values of industry profits:

- Π^b is the cooperative equilibrium level of joint profits when both firms discover. This is obtained by substituting the equilibrium values of the information-sharing variables as given by Theorem 4 into the joint profit function.
- Π^w are the cooperative equilibrium joint profits when just one firm discovers. This is obtained by substituting the equilibrium value of the information-sharing variable as given by Theorem 5 into the joint profit function.
- $\Pi^0 = \Pi(0, 0)$ are industry profits when neither firm has discovered.

Notice that $\Pi^w = \underset{0 \le \sigma^w \le \bar{\sigma}}{Max}\, \Pi(1, \sigma^w) \ge \Pi(1, 0) > \Pi(0, 0) = \Pi^0$. However, at this level of generality we cannot say whether $\Pi^b \gtreqless \Pi^w$.

The RJV now has to choose the discovery probability—and hence the amount of R&D—of each of the two firms, so as to maximise expected joint profits:

$$\phi(p_1, p_2) \equiv p_1 p_2 \Pi^b + p_1(1 - p_2)\Pi^w + p_2(1 - p_1)\Pi^w + (1 - p_1)(1 - p_2)\Pi^0 - c(p_1) - c(p_2)$$

There are various possible types of solution to this problem:

(i) the RJV may have both firms undertake equal amounts of R&D;
(ii) it may have both firms undertake R&D but have them doing different amounts;
(iii) in a more extreme version of (ii) it may concentrate all its R&D in just one firm.

Much of the literature just assumes that the solution is of the first type. However this ignores one of the potential benefits of RJVs which is that they might be able to undertake R&D more efficiently by concentrating all the R&D in one lab and so avoiding needless duplication. By contrast Katz [1986] assumes that the solution is of type (iii).

Here, rather than assuming a solution type we want to determine it and then explain the amount of R&D that is done given the solution type.

The obvious way to do this would be to seek the general solution to the above maximisation problem. However this line of attack is complicated by the fact that we cannot guarantee that this expected industry profit function is everywhere strictly concave.[16] This raises two difficulties: first-order conditions may not characterise local maxima; there may be multiple local maxima.

Rather than undertake a long and detailed analysis of the general problem we confine our attention to solutions of type (i) and type (iii) only and explore the factors that could lead an RJV to operate just one lab, rather than two labs working equally hard.

Suppose then that the RJV operates two labs, each doing the same amount of R&D and so having the same probability p of discovery. The optimal value of p to choose is that which maximises

$$p^2\Pi^b + 2p(1-p)\Pi^w + (1-p)^2\Pi^0 - 2c(p).$$

It is easy to check that this has a unique global maximum $\hat{p}$, $0 < \hat{p} < 1$ satisfying the condition

$$\hat{p}(\Pi^b - \Pi^w) + (1-\hat{p})(\Pi^w - \Pi^0) = c'(\hat{p}). \tag{11}$$

It is also easy to show that $(\hat{p}, \hat{p})$ is a local maximum of the function $\phi(p_1, p_2)$.

Then

$$\hat{V}^2 \equiv \hat{p}^2\Pi^b + 2\hat{p}(1-\hat{p})\Pi^w + (1-\hat{p})^2\Pi^0 - 2c(\hat{p}) \tag{12}$$

is the expected profit for the RJV if it operates two labs at equal intensity.

Suppose instead that the RJV operated a single lab with probability of discovery $P, 0 \leq P \leq 1$. The optimal value of P for the RJV to choose is

[16] For this to be true we would require $(\Pi^b + \Pi^0 - 2\Pi^w)^2 < c''(p_1).c''(p_2) \quad \forall p_1, p_2$.

the one which maximises

$$P\Pi^w + (1-P)\Pi^0 - c(P).$$

Once again it is easy to show that this has a unique global maximum $\hat{P}, 0 < \hat{P} < 1$ satisfying the condition

$$\Pi^w - \Pi^0 = c'(\hat{P}). \tag{13}$$

Then

$$\hat{V}^1 \equiv \hat{P}\Pi^w + (1-\hat{P})\Pi^0 - c(\hat{P}) \tag{14}$$

gives the expected profit of the RJV if it operates a single lab.

The question of whether the RJV operates one or two labs reduces to a comparison of $\hat{V}^1$ and $\hat{V}^2$. To get some insight into what can be said about this, notice that we can write:

$$\begin{aligned} \hat{V}^2 &= \hat{p}^2(\Pi^b - \Pi^w) + \{\hat{p}^2\Pi^w + 2\hat{p}(1-\hat{p})\Pi^w + (1-\hat{p})^2\Pi^0 - 2c(\hat{p})\} \\ &= \hat{p}^2(\Pi^b - \Pi^w) + \{(\hat{p} + \hat{p}(1-\hat{p}))\Pi^w + (1-\hat{p})^2\Pi^0 - 2c(\hat{p})\} \end{aligned} \tag{15}$$

Suppose for the moment that $\Pi^b = \Pi^w$. One interesting case where this would be so is where $\gamma = 0, \bar{\sigma} = 1$ and the solution to the information-sharing problem in section IV(ii) is $\sigma^w = \bar{\sigma} = 1$. For then $\Pi^b = \Pi(1,1) = \Pi^w$. Thus the RJV gets the same payoff whether one firm discovers or both discover. When both discover, the fact that firms have exactly duplicated each other's research prevents either firm from benefitting from anything it might learn from the other; whereas if only one discovers it fully reveals its discovery to the other.

In this case the first term on the RHS of (15) is zero. Consider the second term. Suppose the RJV sets up a single lab and tells it to achieve a probability of success $\tilde{P} = \hat{p} + \hat{p}(1-\hat{p}) > \hat{p}$. This would cost $c(\tilde{P}) = c(\hat{p} + \hat{p}(1-\hat{p})) > c(\hat{p})$. However if

$$c(\hat{p} + \hat{p}(1-\hat{p})) < 2c(\hat{p}), \tag{16}$$

then it would be cheaper to operate a single lab and hence it would necessarily be the case that $\hat{V}^1 > \hat{V}^2$.

There are two factors at work in determining whether or not (16) holds. Having just one lab around avoids the needless duplication of research that arises when both firms discover. However, in order to have the same probability that at last one lab discovers, the single lab has to work harder than does either of the two labs when both are operating and hence will encounter diminishing returns. Whether or not (16) holds depends on the balance of these two factors.

Thus when $\Pi^b = \Pi^w$, it is essentially just R&D cost saving considerations which determine whether the RJV operates one lab or two. When (16) holds, the RJV will be able to achieve its target probability of discovery more cheaply than would be the case in the non-cooperative equilibrium since it can close a lab.

Suppose now $\Pi^b < \Pi^w$. This would typically happen when both firms are in the same industry. What is happening here is that when both discover the industry is so competitive that, despite the fact that both firms have made progress, joint profits are lower than when just one firm discovers.

In this case the first term on the RHS of (15) is negative and this introduces a second reason why the RJV may wish to close a lab—to avoid the competitive pressures that arise when both discover. **Thus the RJV may close a lab for anti-competitive reasons.**

Notice that this second factor is completely independent of the first consideration behind closing a lab. So the second factor could lead the RJV to close a lab even when the cost considerations pointed in favour of running two labs.

Finally, consider the case where $\Pi^b > \Pi^w$. This could arise when γ is large and consequently there are very considerable complementarities between the research discoveries of the two firms. This enables them to make far more progress when they both discover than would be the case when one alone discovers.

In this case the first term on the RHS of (15) is positive, pointing to a reason to keep both labs open in order to reap these gains when both discover. Once again this operates independently of the cost considerations pointed out above and could lead the RJV to keep both labs open even when cost considerations pointed in favour of closing one.

We see than that

(i) cost considerations are **one** of the factors lying behind the RJVs decision as to whether to operate one or two labs and can certainly lead the RJV to reap efficiency gains in carrying out R&D through eliminating a needless duplication of effort;

(ii) however eliminating needless duplication is not the only element of the cost calculation—diminishing returns are an important cost reason for having two labs.

(iii) cost considerations tend to be the dominant factor when (a) research outputs are very close substitutes; (b) firms are willing to share a lot of information;

(iv) the RJV may also close a lab for anti-competitive reasons—to prevent its having to face a very competitive situation when both firms discover;

(v) the RJV may wish to keep both labs open in order to exploit very strong complementarities between the research output of the two firms.

Finally, having thus determined whether the RJV operates one lab or two, we can use equations (11) and (14) to determine the corresponding probabilities of discovery (R&D outputs) chosen by the RJV. These can then be compared with the corresponding probabilities of discovery in the non-cooperative equilibrium. The generality of the framework employed here prevents any immediate comparison, though undoubtedly more could be said by following the rest of the literature and putting a great deal more structure into the model.

V. CONCLUSIONS

In this paper we have presented a modelling framework for analysing how successful research joint ventures might be in addressing **all** the market failures that arise in R&D. In order to do this properly we have had to make spillovers endogenous. This in turn has necessitated our introducing a lot of distinctions and features, not all of which are typically recognised in models which treat spillovers as exogenous. The resulting modelling framework is extremely rich, and generates a number of original conclusions.

In particular, an important finding of this paper is that there are a number of respects in which RJVs may sometimes act in an anti-competitive fashion. This arises when the RJV deliberately generates asymmetric outcomes in terms of information sharing or R&D inputs. Our framework can predict the circumstances under which this anti-competitive behaviour can arise. We thus have the beginnings of an analytical framework for the anti-trust treatment of RJVs. The possibility of anti-competitive outcomes is precluded in the existing literature which focuses on symmetric outcomes.

An issue that now arises is the relationship between this paper and the existing empirical literature. There are two such literatures which could be considered relevant.

The first is the empirical literature on the estimation of spillovers to which we referred at the start of the paper. There are, however, a number of difficulties with relating this to our model. The first is that this literature does not distinguish between firms which are in research alliances and those which are not. Secondly, by looking at the link between one firm's R&D and another's cost reduction, these studies conflate the magnitude of spillovers and the function $\tau(.)$ and so do not provide direct evidence on spillovers. Finally, these studies operate entirely on the assumption that spillovers are exogenous. By providing a theoretical framework for analysing endogenous spillovers our paper provides the basis for a considerable amount of new empirical work on the direct estimation of spillovers and the determination of their magnitude.

The second literature is that on RJV formation. This is much smaller, and does not directly examine the amount of information-sharing inside and outside RJVs. Nevertheless it provides some indirect support for our model.

For example Katsoulacos [1993] reports that the majority of joint ventures supported by EU RTD programmes are between firms which are in different industries. Notice that these programmes give firms an R&D subsidy if they share information. Our theory predicts that such firms would have fully shared information even in the absence of a cooperative agreement. So, if the EU subsidises them for something they would have done anyway, it is hardly surprising that they form the bulk of successful applicants.

In a similar spirit Kesteloot and Veugelers [1997] report the following.

- '. . . research alliances tend to be organised more frequently between partners from different nationalities'. This again is consistent with our finding that co-operative agreements are more likely to share information when they operate in separate markets.
- '. . . alliances between partners that are technologically not related, involve significantly less research activities' and 'research alliances are significantly more asymmetric than other alliances', both of which they interpret as evidence that research alliances are involved in 'a more intense quest for complementarities'

While our modelling framework is in many ways very general, there remain a number of important directions for future theoretical and policy extensions. On the theoretical front there is a need for extending the analysis to the case of n firms. In terms of policy we need to undertake an explicit welfare evaluation of the effects of various policy instruments—R&D subsidies; RJV subsidies; intellectual property rights etc. Some of this is contained in a sequel to this paper.

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