

Innovation Spillovers and Technology Policy

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ABSTRACT. – We examine a model of R&D competition and cooperation in the presence of spillovers. However, unlike virtually all the literature, we treat these spillovers as endogenous and under the control of firms. We show that it is then essential to make a number of distinctions that are ignored in the literature. In particular we need to distinguish between the amount of R&D that firms do and the amount of spillover they generate; between *information sharing* and *research coordination*; between each of the latter and cooperation; between *substitute* and *complementary* research paths; between firms being located in the same industry or in different industries. These distinctions matter because, as we show, *coordination* can arise without *cooperation* (different industries, complementary research, research design) while *cooperation* need not induce *information sharing* (same industry, substitute research, information sharing). In many cases, however, allowing cooperation is sufficient to induce full *information sharing/research coordination*, in which case the justification, if any, for a technology policy that takes the form of an R&D subsidy lies in encouraging firms to undertake more R&D. Our analysis suggests that cooperative arrangements between firms may often produce too little R&D, and therefore that R&D subsidies can be justified – but not to correct information problems, but other market failures in the amount of R&D firms choose to do.

Les Spillovers d'innovations et la politique de technologie

RÉSUMÉ. – Nous examinons un modèle de concurrence et de coopération en R&D quand il y a des spillovers. Contrairement à ceux que nous trouvons dans la littérature, nous traitons ces spillovers comme étant endogènes et étant contrôlés par des entreprises. Nous démontrons qu'il est nécessaire de faire un nombre de distinctions dont la littérature ne tient aucun compte. En particulier on a besoin de distinguer : la quantité R&D que font les entreprises et la quantité de spillovers qui sont ainsi produites ; entre la participation d'information et la coordination de la recherche ; entre les lignes de recherche qui sont substituées et ceux qui sont complémentaires ; entre les situations où les entreprises se trouvent dans les même secteurs ou dans les secteurs différents. Ce sont des distinctions d'importance parce que, comme nous démontrons, il est possible d'avoir la coordination sans aucune coopération (ce qui arrive quand il y a des secteurs différents et la recherche complémentaire) tant que la coopération ne doit pas nécessairement produire la participation d'information (ce qui travaille dans la même industrie avec la recherche de substitution). Cependant, il est souvent le cas que le droit de coopérer peut produire la pleine participation d'information et coordination de recherche, le cas échéant, la justification (s'il y en a) pour une politique de technologie sous la forme d'une subvention de R&D est d'encourager les entreprises de faire plus de R&D. Notre analyse suggère que les rapports coopératives entre entreprises ne produisent que peu de R&D et, de cette manière, on peut justifier les subventions de R&D non pas pour corriger les problèmes d'information, mais plutôt pour corriger d'autres échecs du marché en ce qui concerne la quantité de R&D que font les entreprises.

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1 Introduction

In this paper we develop a model of oligopolistic R&D rivalry and cooperation in the presence of R&D spillovers. However, in contrast to virtually all the existing literature our focus is on the case where firms choose their spillover parameters **endogenously**. Now as soon as we allow this possibility, it turns out to be critical to make a number of distinctions that are typically not made in the literature.

We usually think of spillovers as arising through one firm's acquiring information about the research discoveries of the other. There are two factors that will bear on the extent of this spillover: the amount of information acquired (quantity of information), and the usefulness of that information to the acquiring firm (quality of information). In principle both of these facets of the spillover are under the firms' control, so when, as here, we think of these spillovers being endogenously determined by firms, we need to be clear about what is being chosen. We will show that this matters by focussing on two polar cases. The first is that of a pure **information sharing** spillover where it is the quantity of information that passes between firms that is being chosen, implicitly assuming that it is useful and that there is no scope for choosing the research design. The second is that where firm's choose their **research design** in order to control the quality of information acquired by the other firm. In this case we implicitly assume that firms have no control over the quantity of information that passes between them.

Second we show that it matters whether the spillover arises between firms that are operating in the **same industry** or in **different industries** since this will crucially affect the private incentives to give potentially beneficial spillovers to another firm. If firms operate in completely separate industries then each has nothing to lose from having the other firm benefit from a spillover from itself, whereas if they are in the same industry then, if one firm alone has made a discovery, it can be damaging to have its rival receive a beneficial spillover.

Third it is important to distinguish between the case where the research that is being undertaken by one firm is a **substitute** or a **complement** for that undertaken by the other. Again this affects our understanding of the incentives to create spillovers. In the **substitute** case firms are essentially undertaking the same research, and will consequently make the same discovery. Thus if *both* firms make a discovery then neither can benefit from any spillover, though one firm can benefit from the other's when it has not itself discovered. When research is **complementary**, then one firm's discovery can be of benefit to the other, and is indeed likely to be most beneficial when they have both made a discovery. Notice that this distinction relates to the previous one in that if firms are operating in completely different industries they will not be undertaking substitute research whilst if they are operating in the same industry they may be undertaking substitute or complementary research.

Finally it is important to distinguish between **cooperation** and **information sharing/coordinating research design**. Just because firms

choose to cooperate (maximise joint profits) it does not necessarily mean that they will choose to share information or coordinate research design – and we will show that there are cases where indeed cooperation does not induce information sharing/research coordination. Equally, the fact that firms choose not to cooperate does not mean that they will not share information or coordinate their research, and again we will show that full research coordination can arise even when firms do not cooperate.

One important motivation for studying a model with endogenous spillovers is to provide a framework for examining **technology policies** that take the form of subsidies to information-sharing (or result-sharing) research joint-ventures (RJVs) – a type of policy that is particularly common in the EU Commission. Notice that there are two parts to the policy: the allowance of cooperative arrangements between firms, and the subsidy to R&D. In order to examine the rationale for such a policy we need to understand what incentives firms may or may not have to share information or coordinate research design in the absence of any policy.

Now in recent years there has been a growing interest among economists in the potential role of research joint ventures (RJVs) in allowing firms to internalise R&D spillovers, coordinate their research activities, and achieve higher R&D output (see, for example, KATZ [1986]; D'ASPREMONT *et al.* [1988]; KATZ and ORDOVER [1990]; SUZUMURA [1992]; BEATH and ULPH [1989]; MOTTA [1992a, 1992b]; KESTELOOT and DE BONDT [1993]). In this literature spillovers are typically modelled as follows. Assuming a duopoly producing a homogeneous product, the unit cost of firm i is taken to depend on its own R&D, x_i , and the R&D of its rival, x_j , via an exogenously given spillover parameter δ . Thus if the unit cost of firm i is c_i , then $c_i = A - x_i - \delta x_j$, $A > 0$, $0 < \delta \leq 1$. Within this framework an RJV is thought of as involving the firms in setting their R&D levels cooperatively to maximise joint profits. In some formulations (for example, D'ASPREMONT *et al.* [1988]) it is assumed that the same spillover parameter applies to the RJV as in the non-cooperative equilibrium, while in others (for example, BEATH and ULPH [1989], MOTTA [1992b] and CREPON *et al.* [1992]) it is assumed that the RJV can automatically achieve full information-sharing/research design coordination ($\delta = 1$). Notice that this also means setting cooperatively the total spillovers δx so, even though cooperation is modelled as being on R&D investment levels (and not on the spillover parameter), RJVs do serve as a spillover internalisation device.

By treating spillovers exogenously these models conflate the decision to invest in R&D with that on information sharing/research design and they also conflate the latter decision with that of cooperation. The first conflation means that these models cannot deal with the fact that we have to deal potentially **with two distinct market failures**: that associated with the R&D investment levels and that associated with the level of information revelation.

To analyse what happens when we endogenise the spillover parameter, we are going to follow the existing literature by focusing on the case where there are just two firms that might potentially form an RJV but allow these firms to be located either in the **same** industry, or in **different** industries and to pursue either **complementary** or **substitute** research. We examine

three types of equilibria. In the **non-cooperative equilibrium** firms choose their R&D and spillover parameters independently. In the **cooperative equilibrium** firms choose their R&D and spillover parameters to maximise joint profits, but there is no subsidy to R&D. Third we consider the **social optimum**. Here a social planner chooses the R&D levels and spillover parameters to maximise social surplus. We can thus explore what market failures arise in terms of both the amount of R&D that is undertaken and in the extent of information sharing/research design coordination; We can examine how far these would be corrected by simply allowing cooperative arrangements without any subsidy.

We show the following:

- When firms operate in the *same industry* pursuing *substitute research*, then, when the spillover takes the form of *information sharing* the *non-cooperative* equilibrium involves no information sharing. When firms cooperate they may still decide not to share information. **Thus cooperation need not involve any information sharing.** When the *cooperative equilibrium* does indeed entail no information sharing then cooperation involves less R&D spending than in the non-cooperative equilibrium. The *social optimum* requires full information sharing. When the *cooperative equilibrium* produces full information sharing then it typically does not produce enough R&D so an R&D subsidy is justified, but not to correct any market failure on information sharing. However, when the *cooperative equilibrium* produces no information sharing, then an R&D subsidy may not be able to produce the social optimum, since the subsidy required to induce full information sharing may be larger than that required to correct the R&D failure.

When firms operate in the *same industry* but pursue *complementary* research paths then much the same qualitative conclusions go through as in the above case (so this latter case is not examined in the paper). Thus the fact that research paths are complementary is not in itself sufficient to induce full information sharing under cooperation.

- When firms operate in different industries, pursuing complementary research, and the spillover takes the form of *research design coordination*, then the non-cooperative equilibrium produces full coordination. **Thus full coordination can arise without cooperation.** (Though not discussed here it can be shown that the same result holds with information sharing spillovers). *Cooperation* produces full research design coordination (and full information sharing), and a higher level of R&D spending than under *non-cooperation*. However, if we compare the *cooperative equilibrium* to the *social optimum*, then, while cooperation produces the optimal degree of coordination, in a wide class of cases the level of R&D spending will be too low, so there could be some justification for an R&D subsidy.

The structure of the paper is as follows: in Section 2 we set out the generic model that we use in the rest of the paper. The bulk of the analysis comes in Sections 3 and 4 where we focus on two opposing cases. Section 3 considers the case where the firms operate in the *same industry* pursuing *substitute research* and there are *information sharing* spillovers while Section 4 considers the polar opposite case where firms are

in *independent industries* pursuing *complementary research* and the spillover takes the form of *research design* coordination. Section 5 concludes.

2 The Generic R&D Model

2.1. Types of Spillover, Types of Equilibria and order of decisions

As noted in the introduction, we will distinguish between spillovers that arise from *information sharing* and those from *research design coordination*. However, the distinction really only matters in the *non-cooperative equilibrium*. To see this let us consider each of the three types of equilibrium in turn.

- *Non-cooperative*

Here the two firms choose their levels of R&D and their spillover parameters independently. This is modelled as a two-stage decision process, and, as de FRAJA [1991] has noted, the order in which the decisions get taken can matter. It is this ordering of decisions which reflects the distinction between the two types of spillover.

When the spillover takes the form of *information sharing*, then, since firms can only share information once they have made a discovery, it is natural to think of their first deciding how much R&D to do and then, once they have made a discovery, choosing how much information about this discovery to reveal. So here the R&D is chosen first and then the spillover parameter.

When the spillover is controlled through the choice of *research design* then clearly this has to get determined before deciding how intensively to pursue the research, so here the spillover parameter is chosen first, and then decisions are taken about the amount of R&D.

- *Fully Cooperative in Absence of Subsidy*

Here there is no R&D subsidy, but firms privately decide to cooperate and choose both R&D and spillovers to maximise joint profits. The assumption is that by cooperating firms can enter into some binding agreement on both R&D and the spillover parameter and therefore, in reaching the agreement, these two variables are chosen simultaneously. Hence the previous distinction is no longer applicable.

- *Social Optimum*

Here if a social planner can exercise control over the R&D levels and the degree of spillover, it is natural to think of these as being chosen simultaneously to maximise total surplus. Once again the distinction between the nature of the spillover is no longer applicable.

So let $\delta = (\delta_1, \delta_2)$ be the spillovers. Then, generally, we will indicate the profit of firm i as follows:

$\pi_i^t(\delta)$ -profits of i if both firms discover;

$\pi_i^w(\delta)$ -profits of i if it alone discovers;
 $\pi_i^\ell(\delta)$ -profits of i if the other firm alone discovers;
 π_i^0 -profits of i if neither firm discovers.

2.2. The R&D Process

We model R&D as a stochastic process. The amount of R&D chosen by each firm simply determines the probability that it will make a discovery, which is independent of that of the other firm, so there is a chance that both will discover, that each alone will discover, and that neither will discover. This is true whether firms operate in a cooperative or non-cooperative environment. To set out the R&D model in more detail, we concentrate now on the non-cooperative equilibrium.

When firms act non-cooperatively they each choose their R&D taking as given the spillover parameters, and hence the profits that they will make contingent on the various possibilities that one and/or the other makes a discovery. This is because either spillovers have been chosen in the previous period (as in the case of research design) or, when spillovers will be chosen in the next period (as with information sharing) their value will be 0 or 1 independently of R&D (as we show below).

Throughout the analysis we will use the probability of discovery as the choice variable and model the R&D technology through a cost function, $c(p)$ giving the amount a firm has to spend on R&D to achieve a probability p . We assume

$$\begin{aligned}
 &c(0) = 0, \quad c'(0) = 0; \\
 &\forall p, \quad 0 < p < 1, \quad c'(p) > 0; \quad c''(p) > 0 \\
 &c(p), \quad c'(p) \rightarrow \infty \quad \text{as } p \rightarrow 1
 \end{aligned}$$

where the first part of the assumption guarantees that as long as the innovation is profitable a firm will choose to spend a positive amount on R&D, while the latter part guarantees that no firm would end up innovating for sure¹.

The archetypal non-cooperative model is therefore that in which the objective function of firm 1 is:

(1)

$$V_1 = p_1 p_2 \pi_1^t + p_1 (1 - p_2) \pi_1^w + p_2 (1 - p_1) \pi_1^\ell + (1 - p_1) (1 - p_2) \pi_1^0 - c(p_1)$$

The profits that appear in this expression will depend on the spillover parameters chosen by each of the two firms. There is an analogous function for firm 2.

1. A functional form that satisfies all these conditions is:

$$c(p) = -\log(1 - p) - p, \quad \text{so } c'(p) = \frac{p}{1 - p}, \quad c''(p) = \frac{1}{(1 - p)^2}$$

Let

$$(2) \quad A = (\pi_1^t - \pi_1^\ell); \quad B = (\pi_1^w - \pi_1^0); \quad C = (\pi_2^t - \pi_2^\ell); \quad D = (\pi_2^w - \pi_2^0)$$

Then the first-order conditions for each of the two firms are:

$$(3) \quad Ap_2 + B(1 - p_2) = c'(p_1)$$

$$(4) \quad Cp_1 + D(1 - p_1) = c'(p_2)$$

A and C are the *competitive threats* of the two firms – that is they show the increase in profits a firm will obtain if the other firm has already innovated. They determine the best response R&D choice by each firm when the other firm's probability of discovery is 1. B and D are the *profit incentives*—that is they show the increase in profits that a firm will obtain if the other firm has not innovated. They determine the best response choice of R&D by each firm when the other firm's probability of discovery is zero². Each firm's optimal p is a strictly increasing (decreasing) function of the other firm's if its *competitive threat* is greater (less) than its *profit incentive*. It is straightforward to show that given our assumptions on $c(p)$ the model has a unique stable solution.

Having set out the basics of the model, we now analyse in detail the outcomes in each of two basic cases.

3 Same Industry, Substitute Research, Information Sharing Spillover

3.1. Basic Constructs for the Same Industry/Substitute Research Case

As already mentioned we assume symmetry³ between firms (so whenever it is convenient we drop subscripts). The basic constructs for the individual firms can be expressed through the following assumptions on their profit functions:

Assumption 1: Profits if both firms discover are independent of spillovers, and equal to π^t , reflecting the fact that since the discoveries are effectively

2. See, for example, BEATH, KATSOUACOS and ULPH [1991, 1992] for a more detailed discussion of the role these two incentives play in the theory of strategic R&D competition.

3. As mentioned by one of the referee's in general we need not expect symmetric outcomes even when firms cooperate.

identical, in this case each firm neither gains nor loses from any spillover. Of course, profits each firm makes if no one discovers are also independent of spillovers and equal to π^0 .

Assumption 2: Profits from winning, $\pi^w(\delta)$ are strictly decreasing in δ whilst profit from losing, $\pi^\ell(\delta)$, are strictly increasing in δ .

Assumption 3: We assume that

$$(5) \quad \pi^w(0) > \pi^t > \pi^0 > \pi^\ell(0)$$

Notice the following:

- The innovation is profitable in that if both firms discover their profits (π^t) will be higher than in the initial position when neither has discovered.

- Each firm's profits are greatest if it alone is the sole innovator and it gives no spillover to its rival, since then the innovator can increase its market share while the other firm loses market share and so finds their profits below those it makes if neither innovates (Assumption 3).

However, precisely because each firm is engaged in identical research and produces a homogeneous product, any spillover from the successful innovator to the rival enables the rival to close the gap on the innovator, thus reducing the profits of the innovating firm and increasing those of the non-innovating firm (Assumption 2). Indeed, we would expect that in the limit, as the spillover tends to 1, each firm's profits will tend to those it would have made had both firms succeeded in making a discovery. Thus in this case the model contrasts with the *independent industry/complementary research* case (examined below) where we must allow for the possibility that a non-innovating firm may not gain anything from the information gleaned from its rival, and certainly would not gain as much from the innovation as the innovating firm.

For society we assume that:

Assumption 4: Analogously with profits, S^t , the total surplus in the industry if both firms innovate and S^0 , the total surplus in the industry if neither firm innovates, are independent of spillovers.

Assumption 5: The total surplus in the industry if a single firm innovates and gives a spillover δ to its rival, $S^s(\delta)$, is strictly increasing in δ .

Assumption 6: We assume

$$(6) \quad \begin{aligned} S^t &> S^0; & S^t &> S^s(0); \\ S^t &> 2\pi^t; & S^0 &> 2\pi^0; & S^s(0) &> \pi^w(0) + \pi^\ell(0) \end{aligned}$$

Hence total surplus is higher when both firms innovate than is the case either in the absence of any innovation, or in the case where one firm alone innovates (and there is no spillover). Also total surplus always exceeds total profits.

3.2. Non-Cooperative Equilibrium

Since we are dealing with a case where the spillover takes the form of *information sharing*, the non-cooperative equilibrium takes the form of a

two-stage game in which firms first choose their R&D and then, when they have made a discovery, decide how much of the information they have discovered to reveal. In the case where one firm alone makes a discovery, it is clear from the specification of profits that since the discovering firm's profits are strictly decreasing in its own spillover, it will choose to reveal nothing. In the case where both firms make a discovery, since they have both discovered effectively the same thing, they have nothing to gain or lose from any information revelation so we can take the spillover parameter to be zero. Thus we have:

Result 1: The non-cooperative equilibrium spillover parameters will be zero whenever firms compete in the same market engage in substitute research and the spillover takes the firms of information sharing.

Let us therefore turn to the first stage of the game – the choice of R&D. It is easy to check that when the spillover parameters are both zero the competitive threats facing the two firms are $A = C = \pi^t - \pi^\ell(0)$, while the *profit incentives* are $B = D = \pi^w(0) - \pi^0$. Therefore the symmetric non-cooperative equilibrium value of p is given by

$$p[\pi^t - \pi^\ell(0)] + (1-p)[\pi^w(0) - \pi^0] = c'(p)$$

For later purposes, it helps to write this as

$$(7) \quad [\pi^w(0) - \pi^0] + p[\pi^t + \pi^0 - \pi^w(0) - \pi^\ell(0)] = c'(p)$$

It is important to note that the *competitive threat* can be greater or less than the *profit incentive* so the two firms' R&D levels can be strategic complements or strategic substitutes.

3.3. The Cooperative Equilibrium

Here p and δ are chosen to maximise expected profits per firm, *i.e.* so as to maximise

$$(8) \quad V(p, \delta) = p^2 \pi^t + p(1-p)[\pi^w(\delta) + \pi^\ell(\delta)] + (1-p)^2 \pi^0 - c(p)$$

We can see immediately that:

Result 2: If total industry profit when just one firm innovates (the term in square brackets) is increasing in δ then the cooperative equilibrium value of $\delta = 1$ ⁴.

4. This would certainly be the case if $\pi^w(\delta)$ and $\pi^\ell(\delta)$ are linear functions of δ , specifically if $\pi^w(\delta) = \delta\pi^t + (1-\delta)\pi^w(0)$, and $\pi^\ell(\delta) = \delta\pi^t + (1-\delta)\pi^\ell(0)$, and

$$2\pi^t > \pi^w(0) + \pi^\ell(0)$$

so that industry profits are greater when both firms have the new technology than when only one alone has it. We should stress here that this linearity assumption is not necessary and can be replaced by assumptions of convexity or monotonicity (that will hold in a very wide class of cases) without changing any of the results or insights of the paper (so, essentially, all we are missing is the case where profit takes an interior maximum).

The cooperative equilibrium value of p if Result 2 holds is given by:

$$(9) \quad 2(1-p)(\pi^t - \pi^0) = c'(p)$$

Result 3: In the opposite case, that is, where total industry profit is decreasing in δ then the cooperative equilibrium value of $\delta = 0$, and the cooperative equilibrium value of p is given by:

$$(10) \quad (\pi^w(0) + \pi^\ell(0) - 2\pi^0) + 2p[\pi^t + \pi^0 - (\pi^w(0) + \pi^\ell(0))] = c'(p)$$

Result 3 illustrates a case where cooperation does not lead to any information revelation. This substantiates the point made in the introduction that when we endogenise spillovers we have to be very careful to distinguish between these two notions⁵.

To undertake a comparison of the cooperative and the non-cooperative equilibria, it is useful to begin with this latter case, for then there is no information revelation in either equilibrium, and the only difference is in the R&D levels. Notice that since, by assumption, $\pi^\ell(0) < \pi^0$, the first term on the LHS of (10) is smaller than the corresponding term on the LHS of (7). Given this and the fact that the second constant term on the LHS of equation (11) is negative and twice the value of the same term in equation (7) clearly implies that:

Result 4: In the present case of same industry, substitute research and information sharing spillovers, if industry profits when just one firm innovates are decreasing in δ , cooperation will result in firms investing less in R&D than when acting independently⁶.

In the opposite case where total profits are increasing in δ when one firm innovates, under cooperation firms will choose maximum information revelation ($\delta = 1$). In this case, comparing equations (7) to (9) we see that:

Result 5: When total industry profits are increasing in δ when one firm innovates, the probability of discovery can be greater, equal or smaller when

5. When firms engage in **complementary research** then because once again an innovating firm's profits will be a decreasing function of its own spillover, in the non-cooperative equilibrium each firm will set its (information sharing) spillover to zero. However because now (with complementary research) firms have more to gain from sharing information if they **both** innovate it is more likely that under cooperation $\delta = 1$. That is, under cooperation δ will be certainly unity if the condition in Result 2 above holds, but it may also be unity even if this condition does not hold. To see this, note that, with complementary research, π^t will be an increasing function of δ . Thus $V(p, \delta)$ —equation (8)—may be then increasing in δ (and we may get $\delta = 1$) **even if** the term in square brackets (*i.e.* total profit) is decreasing in δ .

6. This result is consistent with that by D'ASPROMONT and JACQUEMIN [1988]. In their model if the exogenous spillover parameter is small (less than 0.5) cooperation results in a decrease in R&D. Here, on the other hand, with linear profit functions, **for as long as** $2\pi^t < \pi^w(0) + \pi^\ell(0)$ **firms will choose not to reveal any information under a cooperative agreement** ($\delta = 0$) **and will choose to invest less on R&D than they would have done independently.**

firms cooperate relative to its value when they act independently ⁷.

3.4. The Social Optimum

The problem is to choose p and δ to maximise total expected surplus in the industry where this is given by:

$$(11) \quad \bar{W}(p, \delta) = p^2 S^t + 2p(1-p) S^s(\delta) + (1-p)^2 S^0 - 2c(p)$$

where $S^s(\delta)$ has been defined above as the social surplus when a single firm innovates and the degree of information revelation is δ . Given that $S^t > S^s(0)$, $S^s(\delta)$ is strictly increasing in δ and so therefore is expected social surplus. Thus:

Result 6: It is socially optimal to engage in maximum information revelation (the socially optimal value of $\delta = 1$).

With $\delta = 1$, from (11), the socially optimal value of p is defined by the first-order condition:

$$(12) \quad (1-p)(S^t - S^0) = c'(p)$$

where we have used the fact that $S^s(1) = S^t$ ⁸.

There are clearly two distinct distortions that the market may produce that may justify policy intervention. First the market may under cooperation generate less than optimal information revelation (a value of δ that is less than unity). Secondly, even when there is maximum information revelation under cooperation, the amount of R&D and hence probability of success may be less than at the socially optimal level.

Consider first the case where total industry profit when one firm innovates is increasing in δ so under cooperation firms will choose maximum information revelation ($\delta = 1$) and the only market distortion can come from suboptimal p . In this case equilibrium p is given by (9) which can be rewritten in the presence of a subsidy as

$$(13) \quad 2(1-p)(\pi^t - \pi^0) = c'(p)(1-s)$$

7. Also note that in the latter case where $\delta = 1$ under cooperation each firm gets π^t either when both discover or one discovers. In the first event that occurs with probability p^2 there is needless duplication. The second event occurs with probability $2p(1-p)$. Thus the probability of discovery is $2p - p^2 = p(2-p)$. The R&D cost is $2c(p)$. The total R&D cost of getting the same probability with just one active R&D laboratory is $c(p(2-p))$. So when $c(p(2-p)) > 2c(p)$ it is better to have two active R&D laboratories whilst in the reverse case it is better to have one active R&D laboratory. If $c(p) = -p - \log(1-p)$ then $c(p(2-p)) > 2c(p)$ and we can assume that both firms will have active R&D laboratories. If however $c(p) = p^2$ then $c[p(2-p)] < 2c(p)$ if $p > 2 - \sqrt{2}$ and so for large p it is best to have only one R&D laboratory active. We will assume that $c(p) = -p - \log(1-p)$ so it is optimal to have two laboratories active.

8. There is again the issue of whether to have 1 or 2 R&D laboratories and the same conditions govern this as for private firms, so given above cost function it is optimal to have two laboratories.

Comparing (13) to (12) we see that with $s = 0$ optimum p will be greater (equal, smaller) than equilibrium p if $S^t - S^0$ is greater (equal, smaller) than $2(\pi' - \pi^0)$. So we have:

Result 7: If total industry profit when one firm innovates is increasing in δ , in the linear demand case where $S^t - S^0 = 4(\pi' - \pi^0)$ the social optimum is greater than the equilibrium value of p and the optimum subsidy is positive—indeed it should be 50%.

On the other hand, if total industry profit is decreasing in δ then the cooperative equilibrium value of $\delta = 0$, and the cooperative equilibrium value of p is given by (10). So the market is now generating the wrong amount of information revelation and, as a comparison of (10) and (12) shows, the cooperative equilibrium value of p will in general be different from the optimum value of p , \hat{p} , though, at this level of generality it is impossible to say whether p is greater than or less than \hat{p} . That is, there are now two market failures, and as intuition also suggests, it may not be possible to correct them and achieve the optimum outcome with the single instrument of an R&D subsidy ⁹.

4 Independent Industry, Complementary Research, Research Design Spillover

In this section we consider a case when the spillover arises through *research design coordination*. As we pointed out in section 2, in this case in the non-cooperative equilibrium, we think of the spillover being chosen first and the R&D level second.

In the case where firms are undertaking substitute research, the research design is essentially fixed, and the only form of spillover is *information sharing* so we will focus our attention in this section on the case where firms are undertaking complementary research. Further we will assume that firms operate in different industries.

4.1. Basic Constructs for the Independent Industry/ Complementary Research Case

To start with we will make the following assumptions about the firms' profit functions:

Assumption 7: Profits π^w of either firm if it alone innovates and profits π^0 of either firm if neither firm innovates are independent of spillovers.

Assumption 8: Profits $\pi^t(\delta)$ of firm i if both innovate and it gets spillover δ from the other firm are strictly increasing in δ . Profits $\pi^\ell(\delta)$ of firm i if

the other firm alone innovates and it again gets spillover δ from the other firm are non-decreasing in δ .

Assumption 9: We assume that

$$(14) \quad \pi^t(1) > \pi^w > \pi^\ell(1) \geq \pi^0$$

These assumptions capture the following features.

- If a single firm innovates it gains nothing from the rival firm's R&D (since it has not innovated) but loses nothing by revealing information to its rival (since the other firm is in a different industry).

- If a firm fails to innovate then, precisely because the research is on different lines, the non-innovating firm may gain nothing from the discovery of the rival firm—even if the spillover is 1. However although we also allow the possibility that the non-innovating firm will gain something from the spillover from the innovator, we assume that even when the spillover is 1 the non-innovating firm will not gain as much from the discovery as the innovating firm, thus reflecting the idea that the discovery is best suited to the firm making the discovery.

Indeed although we allow the possibility that a firm might gain from the other firm's spillover, even if it itself has not discovered, we want to assume that:

Assumption 10:

$$(15) \quad \pi^t(1) - \pi^w > \pi^\ell(1) - \pi^0$$

so that what each firm gains from the other firm's innovation is greatest when that firm has itself innovated.

- If both firms innovate, then each can gain from any spillover from the rival firm. In terms of social welfare we assume that:

Assumption 11: The total surplus arising in a *single* industry in which the firm is the sole innovator, S^w , and the total surplus arising in *each* industry i if neither firm innovates, S^0 , are independent of spillovers.

Assumption 12: The total surplus in industry i if it fails to innovate but it receives a spillover δ from a successful discovery in industry j , $S^\ell(\delta)$, is increasing in δ . The total surplus arising in industry i if *both* industries innovate, and there is a spillover δ from a successful discovery in industry j , $S^t(\delta)$, is strictly increasing in δ .

Assumption 13: We assume

$$(16) \quad S^t(1) > S^w > S^\ell(1) \geq S^0$$

and that

$$(17) \quad S^t(1) > \pi^t(1); S^w > \pi^w; S^\ell(1) > \pi^\ell(1); S^0 > \pi^0.$$

Thus society's ranking of the various outcomes in any industry simply reflects the degree of innovation that accrues there and therefore generates the same ranking as industry profits. In particular this means that the final

inequality in (16) is strict if and only if that in (14) is strict. As is usual social surplus in any industry always exceeds industry profits.

4.2. The Non-Cooperative Equilibrium

Consider then a two-stage non-cooperative equilibrium, in which the two firms in the different industries first choose the spillover, and then their level of R&D.

We solve backwards, and analyse first the R&D decisions. On doing the substitutions of the profit expressions into (2) we find that in this case the competitive threats and profit incentives are defined by:

$$(18) \quad A = \delta_2 [\pi^t(1) - \pi^\ell(1)] + (1 - \delta_2) [\pi^w - \pi^0]; \quad B = [\pi^w - \pi^0]$$

and

$$(19) \quad C = \delta_1 [\pi^t(1) - \pi^\ell(1)] + (1 - \delta_1) [\pi^w - \pi^0]; \quad D = [\pi^w - \pi^0]$$

Thus in determining the relative magnitudes of the *competitive threats* and *profit incentives* everything just depends on the relative magnitudes of the two terms in square brackets that appear in the *competitive threats*. Now we can re-write these as

$$\pi^t - \pi^\ell = (\pi^t - \pi^w) + (\pi^w - \pi^\ell); \quad \pi^w - \pi^0 = (\pi^t - \pi^0) + (\pi^w - \pi^t)$$

The second term on the RHS of these expressions is identical, so the only difference lies in the first terms which measure the value to a firm of the other firm's discovery if (i) it itself has discovered, or (ii) it has not discovered. In (15) we have assumed that the former is greater than the latter, so that, as long as there are any spillovers at all, $A - B > 0$ and $C - D > 0$, the *competitive threat* is greater than the *profit incentive*. Thus, in the present case the reaction functions are upward sloping—R&D expenditures are strategic complements (BULOW *et al.*, [1985]).

4.3. The Incentive to Coordinate in the Non-Cooperative Equilibrium

Having determined the optimal R&D decisions of firms, conditional on spillovers, we now have to work out the spillover they will choose—*i.e.* their incentive to coordinate. Let $V_i(\delta_1, \delta_2)$ be the expected value of profits of firm i with the equilibrium choices of R&D conditional on the chosen levels of spillovers.

Thus, for firm 1 we have

$$(20) \quad V_1(\delta_1, \delta_2) = p_1 p_2 [\delta_2 \pi^t(1) + (1 - \delta_2) \pi^w] + p_1 (1 - p_2) \pi^w \\ + (1 - p_1) p_2 [\delta_2 \pi^\ell(1) + (1 - \delta_2) \pi^0] \\ + (1 - p_1) (1 - p_2) \pi^0 - c(p_1)$$

The incentive for *research coordination* in the stage 1 decision is determined by the sign of $\frac{\partial V_1}{\partial \delta_i}$. Using the envelope theorem we have:

$$(21) \quad \frac{\partial V_1}{\partial \delta_1} = \delta_2 [p_1 (\pi_1^t(1) - \pi_1^w) + (1 - p_1) (\pi_1^\ell(1) - \pi_1^0)] \frac{\partial p_2}{\partial \delta_1}.$$

Thus, because each firm's profits are independent of their own spillover parameter, the only effect of firm 1's increasing its spillover parameter can come from the effect that this can have in inducing firm 2 to change the amount of R&D it does—and this will only affect firm 1 if it receives a positive spillover from firm 2. The term in square brackets is unambiguously positive showing that, provided there is any spillover from firm 2, firm 1 gains if firm 2 does more R&D. Moreover an increase in disclosure by firm 1 will raise the competitive threat of firm 2 and so, given that R&D expenditures are strategic complements, this will lead to an increase in its equilibrium R&D level. That is, $\partial p_2 / \partial \delta_1 > 0$ and hence,

$$(22) \quad \frac{\partial V_1}{\partial \delta_1} \geq 0 \quad \text{as } \delta_2 \geq 0$$

Notice also that

$$(23) \quad \frac{\partial V_1}{\partial \delta_2} = \delta_2 [p_1 (\pi_1^t(1) - \pi_1^w) + (1 - p_1) (\pi_1^\ell(1) - \pi_1^0)] \frac{\partial p_2}{\partial \delta_2} + p_1 p_2 \{[\pi^t(1) - \pi^w] + (1 - p_1) p_2 [\pi^\ell(1) - \pi^0]\}$$

Thus an increase in firm 2's spillover has two effects on firm 1's profits. There is the direct effect—the term in curly brackets, which is positive—and there is the indirect effect brought about by the stimulus this gives to firm 2's R&D. As above this is positive if firm 2's spillover is positive. Hence

$$(24) \quad \frac{\partial V_1}{\partial \delta_2} > 0$$

So we can see that there are two Nash equilibria—(0, 0) and (1, 1), though notice that if one firm's spillover is zero, the other firm is indifferent as to which spillover to choose, so there is no guarantee that it would choose also 0. Thus (1, 1) is the only stable equilibrium, and, given (22) and (24) Pareto dominates (0, 0). Thus the natural equilibrium to select here is (1, 1) and so, as our intuition would suggest, firms would be independently willing to go for as much coordination as possible, that is, the non-cooperative equilibrium spillover parameters are both 1. Thus:

Result 8: When firms operate in distinct industries pursuing complementary research and the spillover takes the form of research design coordination then full coordination will be achieved without any cooperation.

4.4. The Complete Non-Cooperative Equilibrium

Knowing that the spillover parameters of both firms will be 1, we can now return to the R&D decision. Setting the spillover parameters means that the

competitive threats and profit incentives of the two firms are identical, and so too is the equilibrium probability of success. If we substitute (18) into (3), then the equilibrium is characterised by

$$[\pi^t(1) - \pi^\ell(1)]p + [\pi^w - \pi^0](1 - p) = c'(p)$$

i.e.

$$(25) \quad [\pi^w - \pi^0] + [\pi^t(1) + \pi^0 - \pi^w - \pi^\ell(1)]p = c'(p)$$

Given our assumptions (especially (15)) both the constant and the coefficient on p on the LHS of (25) are positive.

It is worth noting here that the non-cooperative equilibrium value of p determined by (25) is larger than that where the spillover comes from information sharing (a case we examine in the Appendix). In this latter case firms set $\delta = 0$. That is:

Result 9: The fact that under *research design coordination* firms choose to fully coordinate their R&D gives them a greater incentive to do R&D than in the *information sharing* case where firms do not share any information in the non-cooperative equilibrium.

4.5. The Cooperative Equilibrium

In the absence of any R&D subsidy, the two firms would choose p and δ to maximise expected joint profits, or alternatively (given symmetry), expected profit per firm. Formally then the problem is to

$$(26) \quad \text{MAX } \bar{V}(p, \delta) \equiv p^2 \pi^t(\delta) + p(1 - p)[\pi^w + \pi^\ell(\delta)] + (1 - p)^2 \pi^0 - c(p)$$

Since both $\pi^t(\delta)$ and $\pi^\ell(\delta)$ are non-decreasing in δ while the former is strictly increasing, it immediately follows that:

Result 10: The cooperative equilibrium value of $\delta = 1$. Thus cooperation achieves maximum research design coordination.

Choosing p to maximise expected profits gives

$$(27) \quad [(\pi^w - \pi^0) + (\pi^\ell(1) - \pi^0)] + 2p[\pi^t(1) + \pi^0 - \pi^\ell(1) - \pi^w] = c'(p)$$

If we compare (27) with (25) then we see that the constant term on the LHS of (27) is at least as great as that on the LHS of (25), while, given the assumption expressed by (15), the coefficient on p in (25) and (27) is positive. Hence we have:

Result 11: The cooperative level of R&D spending is certainly greater than that in the non-cooperative equilibrium when firms are in distinct industries engage in complementary research and spillovers take the form of research design coordination.

4.6. The Social Optimum

The problem here is to choose p and δ to maximise total expected surplus in both industries, or, given symmetry, expected surplus per industry. Formally the problem is to choose p and δ to maximise

$$\bar{W}(p, \delta) \equiv p^2 S^t(\delta) + p(1-p)[S^w + S^\ell(\delta)] + (1-p)^2 S^0 - c(p).$$

Since both $S^t(\cdot)$ and $S^\ell(\cdot)$ are strictly increasing in δ it follows that:

Result 12: The social optimum will require $\delta = 1$, that is, full research design coordination. The optimum value of p will therefore satisfy

$$(28) \quad [S^w + S^\ell(1) - 2S^0] + 2p[S^t(1) + S^0 - S^\ell(1) - S^w] = c'(p)$$

Since the cooperative equilibrium and the social optimum involve maximising the total payoff to R&D from both firms it is not surprising that (28) and (27) are formally equivalent with profits just being replaced by social surplus. Although surplus always exceeds profits it is less clear how the surplus differences that appear in (28) compare with the profit differences that appear in (27). However we can prove that ⁹:

Result 13: There will be a very wide range of cases consisting of perturbations around the linear case under which the optimum value of p exceeds that under cooperation and then the optimal subsidy is positive. Note however that the subsidy is not inducing firms to reveal more information than they would have done autonomously—it does not correct a distortion in the degree of spillover—but induces firms to undertake the right amount of R&D investment.

9. If we let $S^w + S^\ell(1) - 2S^0 \equiv k_1 \Psi$, where $\Psi \equiv \pi^w + \pi^\ell(1) - 2\pi^0$ and $S^t(1) - S^0 \equiv k_2 \Omega$, where $\Omega = \pi^t(1) - \pi^0$ then (27) and (28) can be re-written as:

$$(27') \quad \Psi + 2p[\Omega - \Psi] = c'(p)$$

and

$$(28') \quad k_1 \Psi + 2p[k_2 \Omega - k_1 \Psi] = c'(p)$$

If $k_2 \geq k_1 > 1$ then the optimum value of p is unambiguously greater than the cooperative equilibrium. One case where this is definitely true is the following. If the two firms are monopolists in their individual industries, if the demand curves are linear, and marginal costs are constant, then we know that the deadweight loss from monopoly is half monopoly profits, so that $k_1 = k_2 = 1.5$. Indeed, in this case the optimal subsidy to R&D would be 33%.

To see this, notice that when $k_1 = k_2 = 1.5$ we can re-write (28') as $\Psi + 2p[\Omega - \Psi] = \frac{2}{3} c'(p)$. If we compare this with the formula in (27') for the R&D chosen in a cooperative equilibrium we see that this indeed determines the amount of R&D that would be chosen cooperatively if R&D was subsidised by 1/3.

5 Conclusions

We have shown that when we endogenise spillovers in models of R&D competition and cooperation, then it is essential to make a number of distinctions that are often ignored in the literature. In particular we need to distinguish between the amount of R&D that firms do and the amount of spillover they generate; between *information sharing* and *research coordination*; between each of the latter and cooperation; between *substitute* and *complementary* research paths; between firms being located in the same industry or in different industries.

These distinctions matter because, as we have shown, *coordination of the spillovers* can arise without *cooperation* (as in the case of different industries, complementary research, research design) while *cooperation* need not induce *information sharing* (as in same industry, substitute research, information sharing). In many cases, however, allowing cooperation is sufficient to induce full *information sharing/research coordination*, in which case the justification, if any, for the subsidy lies in encouraging firms to undertake more R&D. Indeed our analysis suggests that cooperative arrangements between firms may often produce too little R&D.

There is still much work that requires to be done on the issues raised in this paper. For example, we have considered cooperative arrangements whereby firms cooperate on both R&D and the spillovers. Yet the idea of information-sharing RJVs seems to be limited to cooperation on the spillovers alone. So we need to analyse how such partially cooperative arrangements might operate, and what the rationale might be for limiting firms to cooperation in this dimension alone.

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