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ENDOGENOUS PROTECTION OF R&D INVESTMENTS *

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Abstract

We examine firms' incentives to protect their non-cooperative R&D investments from spilling over to competitors. Contrary to most of the existing literature, we show that the lack of full appropriability can lead to an increase in R&D investments. We also show that even if protection is costless, firms sometimes choose to let their R&D investments unprotected. Our welfare analysis indicates that public policies that promote the dissemination of technological knowledge should be adopted.

Keywords: R&D investments; Spillovers; Protection

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1 Introduction

A firm's technological achievements are typically not confined within the firm's own boundaries.¹ Instead, they often leak out to competitors through a number of channels such as informal talks among employees, mobility of workers, customers, and reverse engineering. According to most of the industrial organization literature on R&D investments, the presence of spillovers, and thus, the lack of full appropriability, dampens a firm's innovation incentives.² This suggests that if a firm could *protect* its R&D investments, that is, if it could make sure that they do not spill over to competitors, its investment incentives would be stronger.

The objective of this paper is to examine whether firms have incentives to protect their R&D investments, as well as whether such protection is socially desirable. To fulfill this objective, we use a simple model in which two competing firms produce differentiated goods. A three-stage game is analyzed. In stage one, each firm decides whether or not it will protect its innovation. In stage two, the two firms invest non-cooperatively in cost-reducing R&D, and in stage three, they compete in quantities.

A firm can protect its innovation in a number of ways. For instance, it can camouflage its processes, it can adopt a close research environment, or it can restrict the mobility of its employees. We assume that patents are not available. This could be the case, for instance, because the type of technological improvements that take place cannot be patented (e.g. changes in product design, upgrading of production systems) or because the cost of patenting is prohibitive for the firms.³ We also assume that if a firm protects its innovation, then its R&D investments do not spill over to its rival. If instead a firm chooses not to take any measures for keeping its technical information secret, then its investments leak out to its competitor at an exogenous spillovers rate.

We show that even when protection is costless, firms sometimes choose to let their knowledge leak out to their competitors. Given that one would expect that a firm is better off when it

¹According to widespread evidence technology spillovers are often present. See e.g. Jaffe (1986), Bernstein and Nadiri (1989), Griliches (1992), and Bloom et al. (2005).

²See d'Aspremont and Jacquemin (1988), Kamien et al. (1992), and De Bondt (1997), among others.

³This assumption is in accordance with empirical studies that have demonstrated that the majority of innovations are not patented (see e.g. Arundel and Kabla, 1998). In addition, it is in line with a number of surveys that have indicated that firms rate secrecy above patents as protection mechanisms (see e.g. Levin et al., 1987, Cohen et al., 2000, Arundel, 2001), as well as with the literature on endogenous spillovers.

only receives spillovers than when it both receives and sends spillovers, our result seems counter-intuitive. Still, the idea behind it is simple. Consider the case in which both firms free-ride on each other's investments, and thus, they have both *incoming* and *outgoing* spillovers. The incoming spillovers encourage a firm's investments since they improve the marginal benefit of its R&D efforts. The outgoing spillovers have instead a negative effect on firm's R&D investments because they strengthen its rival's competitive position. However, the outgoing spillovers can have a positive effect too. In particular, a firm's outgoing spillovers constitute its rival's incoming spillovers, and thus, increase its rival's investments. This can induce, in turn, an increase in the firm's own investments since the firm free-rides on its rival's higher investments. Consider now the case in which only one firm free-rides, and thus, it has only incoming spillovers while its rival has only outgoing spillovers. Clearly, in this case the outgoing spillovers of its rival will only have their negative effect on the rival's investment incentives and thus, the firm will free-ride on lower R&D investments. As a consequence, two-ways spillovers can foster R&D investments more than one-way spillovers, and thus, a firm can be better off being both a sender and a receiver of spillovers than being only a receiver of spillovers. This finding indicates that spillovers are not necessary involuntary and it is consistent with the widespread evidence regarding the existence of spillovers (see e.g. Jaffe, 1986, Bernstein and Nadiri, 1989, Griliches, 1992, and Bloom et al., 2005)

According to our second main result, the lack of full appropriability can enhance R&D investments. In particular, we find that R&D investments can be higher when neither firm protects its investments than when both firms protect their investments. This holds for any spillovers rate when the goods are sufficiently differentiated and for a sufficiently low spillovers rate when the degree of product differentiation takes intermediate values. The intuition is straightforward after our above discussion. When the products are not close substitutes, and thus, the competition is not fierce, the positive effect of outgoing spillovers on investment incentives continues to exist, while their negative effect weakens. At the same time, the incoming spillovers continue to have a positive effect on the investment incentives. Hence, R&D investments can be higher in the presence of two-way spillovers than in the absence of any spillovers.

We show that firm's profits are always higher when both firms do not protect their investments than when they do protect them. This is so because the total cost reduction enjoyed by firms, the

"effective" R&D, is higher in the former case than in the case of protection. Yet, in equilibrium, firms do not always choose to let their information flow. When the competition is strong, the negative effect of the outgoing spillovers dominates and a firm has incentives to unilaterally protect its investments. This clearly implies that firms sometimes end up being trapped into a prisoners' dilemma situation.

Public policies that support the diffusion of technological knowledge, such as policies that facilitate the communication among researchers and the mobility of workers, can help firms escape from the prisoners' dilemma. Such policies are consistent with our welfare result. More precisely, we find that protection is welfare detrimental even when it comes for free. Actually, protection leads not only to lower firms' profits, but also to lower consumers' surplus. This last result is driven by the lower total cost reduction in the case of protection by both firms than in the case of protection by none of the firms. The higher cost in the former case leads to increased prices, and thus, to a lower consumers' surplus.

We consider a number of extensions of our basic model. First, we allow for n firms and show that our results hold true independently of the number of firms. We also show that the firm's incentives to protect their investments decrease with the number of firms. Second, we consider the case in which protection is costly and show that the incentives of firms to leave their investments unprotected as well as our welfare result are reinforced. Third, we examine the role of the efficiency of the R&D technology. We find that the more efficient is the R&D technology the more likely is that the presence of spillovers has a positive effect on investment incentives, and in turn, that the more likely is that firms choose to not protect their investments. Finally, we demonstrate that all our results remain valid under Bertrand competition.

The impact of spillovers in shaping the incentives to conduct R&D has attracted a wide attention in the industrial organization literature. Typically, in this literature, spillovers are treated as exogenous. That is, a fixed portion of a firm's R&D investments is assumed to flow to its competitors through spillovers that cannot be controlled. Exceptions include a number of recent papers by Poyago-Theotoky (1999), Lambertini et al. (2004), Atallah (2004), Gil-Moltó et al. (2005), and

Piga and Poyago-Theotoky (2005).⁴ The first three papers have a completely different approach than ours since they focus on settings in which firms decide ex-post, and not ex-ante, whether they will let their information flow. That is, firms decide about information sharing *after* they invest in R&D. Under this assumption, they find that firms choose to keep their R&D knowledge secret. This is so because, in contrast to our setting, spillovers do not affect the R&D investments that have already been undertaken.

Gil-Moltó et al. (2005) and Piga and Poyago-Theotoky (2005) are more in line with our approach since they consider settings in which firms decide whether they will share their R&D outcomes *before* they invest in R&D. In particular, Gil-Moltó et al. (2005) endogenize spillovers in the case that spillovers result from the similarity of the firms' research designs and Piga and Poyago-Theotoky (2005) in the case that they result from the geographical proximity of firms' locations. In both cases, the degree of spillovers is a function of the distance between the two firms, and thus, it is the same for both firms. This implies that if, for instance, a firm decides to protect its investments, then it has to locate far away from its competitor. By doing so, it will reduce not only its outgoing spillovers but also its incoming spillovers, that coincide in their models. Instead, in our setting a firm can eliminate its outgoing spillovers without necessarily eliminating its incoming spillovers. This difference is also our main one from two recent papers on absorptive capacity by Kamien and Zang (2000) and Wiethaus (2005) in which firms can control the degree of spillovers through the choice of their R&D approach.⁵ In particular, the more idiosyncratic is the R&D approach chosen by a firm the lower are not only its outgoing spillovers but also its incoming spillovers (absorptive capacity effect).⁶ This distinction clearly implies that whereas the aforementioned work fits better in situations where the diffusion of knowledge occurs through proximity (geographical or technological), ours is more appropriate in situations that the diffusion

⁴All these paper consider non-tournament R&D investments. For endogenous spillovers in tournament (or R&D race) models see De Fraja (1993), and Katsoulacos and Ulph (1998).

⁵This is also one of our main differences from the literature on agglomeration and technological clusters where it is assumed that if a firm leaves the cluster then it stops enjoying an additional cost-reduction. See e.g. Belleflamme et al. (2000), and Fosfuri and Rønde (2004).

⁶In another paper on absorptive capacity, Gütner (2003) considers the case in which firms use their internal R&D investments, and not their R&D approach, as a way to influence their degree of spillovers. In his setting, a firm can affect unilaterally only the degree of its incoming spillovers. In our setting instead, a firm can affect unilaterally only the degree of its outgoing spillovers, and it can do so through its protection investments and not through its R&D investments.

occurs through other channels such as workers' mobility and reverse engineering. In this sense, our paper complements the existing literature.

This paper is also related to the literature on spillovers through workers' mobility (see e.g. Fosfuri et al., 2001, Zabojnik, 2002, Motta and Rønde, 2003) according to which if a worker of a technologically advanced firm moves to a rival firm, then it carries with her the firm's knowledge on which the rival firm can free-ride. In contrast to us, this literature has focused primarily on settings in which only one firm innovates. As a consequence, in this literature a single firm decides whether or not it will let its technology flow, and the possible spillovers are only outgoing. One exception is Gersbach and Schmutzler (2003) that allow both firms to innovate and they thus consider both outgoing and incoming spillovers. Our analysis differs from that of Gersbach and Schmutzler (2003) in many respects. In their paper, firms invest in R&D before they try to control their outgoing spillovers, products are homogeneous, and spillovers are assumed to be perfect.

The rest of the paper is organized as follows. In Section 2, we outline the model, and in Section 3, we characterize the impact of protection on R&D investments. In Section 4, we explore the firms' incentives to protect their investments and the welfare implications of protection. Section 5 discusses some extensions of our model, and Section 6 includes some concluding remarks. All the proofs are relegated to the Appendix.

2 The Model

Our model builds upon d' Aspremont and Jacquemin's (1988) seminal framework, henceforth AJ, with two important departures. First, we assume that the two competing firms produce differentiated instead of homogenous products. In particular, we assume that each firm i faces the following (inverse) demand function:

$$p_i(q_i, q_j) = a - q_i - \gamma q_j; \quad i, j = 1, 2, \quad i \neq j, \quad a > 0, \quad 0 \leq \gamma < 1, \quad (1)$$

where p_i and q_i are respectively the price and quantity of firm i 's product, q_j is the quantity of its rival's product, and γ is the degree of product substitutability. Namely, the higher is γ , the closer substitutes the two products are.

Second, we enrich the game analyzed by AJ. In particular, in AJ firms play a two-stage game in which each firm i , first, chooses its level of R&D investments, x_i , and second, it chooses its quantity. We add to this game, an initial stage, in which each of the firms decides whether or not it will protect its innovation.⁷ In the case that a firm, e.g. firm 1, protects its innovation, then in the continuation of the game, there are no spillovers from firm 1 to firm 2. In the case instead, that firm 1 does not protect its innovation, then we assume that the spillovers from firm 1 to firm 2 are equal to an exogenous spillovers rate k , with $0 < k \leq 1$.

Similarly to AJ, the R&D investments undertaken by the firms are cost-reducing.⁸ In particular, the total variable production cost of firm i is:

$$C_i(x_i, x_j, q_i, k_j) = (A - x_i - k_j x_j)q_i, \quad A > x_i + k_j x_j, \quad k_j \in \{0, k\}, \quad (2)$$

where k_j denotes the degree of spillovers from firm j to firm i . In other words, for firm i , k_j denotes the degree of its incoming R&D spillovers, and k_i the degree of its outgoing spillovers.

Finally, the R&D investments are subject to diminishing returns, captured by the quadratic form of their cost, x_i^2 .⁹

It follows from the above, that the profits of each firm i are given by:

$$\pi_i(q_i, q_j, x_i, x_j, k_i, k_j) = (a - q_i - \gamma q_j)q_i - (A - x_i - k_j x_j)q_i - x_i^2. \quad (3)$$

According to the timing of our game, in the last stage of the game, each firm i chooses its quantity q_i . From the first order condition of (3) with respect to q_i , we obtain the Cournot equilibrium quantities for given levels of R&D investments and spillovers rates:

$$q_i(x_i, x_j, k_i, k_j) = \frac{(2 - \gamma)(a - A) + x_i(2 - \gamma k_i) - x_j(\gamma - 2k_j)}{4 - \gamma^2}. \quad (4)$$

⁷In our main analysis, we assume that a firm can protect its investments without incurring any cost. For instance, this could be the case when the protection is achieved by simply including restrictions in the employment contracts that do not allow the mobility of workers to competing firms. In Section 5, we discuss what would happen if protection was costly.

⁸Note that the same results can be obtained with demand-enhancing investments. The analysis is available from the author upon request.

⁹In Section 5, we discuss the role of the cost of R&D investments.

Note, that just like expected, firm i 's output increases with its incoming spillovers k_j and decreases with its outgoing spillovers k_i .

3 R&D investments

In this Section, we obtain the equilibrium R&D investment levels for all the possible realizations of the spillovers rate and examine the impact of protection on firm's innovation incentives.

In stage two, each firm i chooses its level of R&D investments x_i . Substituting (4) into (3), and differentiating with respect to x_i , we obtain the R&D reaction functions:

$$R_i(x_j, k_i, k_j) = \frac{(2 - \gamma k_i)[(a - A)(2 - \gamma) + (2k_j - \gamma)x_j]}{(2 - \gamma^2 + \gamma k_i)[6 - \gamma(\gamma + k_i)]}. \quad (5)$$

Note that the R&D investments can be either strategic substitutes or complements. This can be seen from (5) where the slope of the reaction function depends on the sign of the term that multiplies x_j . It turns out that the R&D investments are strategic substitutes (complements) only for low (high) degree of incoming spillovers. In particular, when k_j is smaller (greater) than $\gamma/2$.

From (5), it follows that the equilibrium R&D levels are:

$$x_i(k_i, k_j) = \frac{(a - A)(2 - \gamma k_i)[\gamma(4 + \gamma(2 - \gamma) - k_j(1 - k_j)) - 2(3 + k_j)]}{(k_i + k_j)[4\gamma^3 - 2\gamma(7 + k_i k_j)] + 4k_i k_j - 36 + \gamma^2(\gamma^4 - \gamma^2 B + \Gamma)}, \quad (6)$$

where $B = 12 + k_i^2 + k_j^2$ and $\Gamma = 4(10 + k_j^2) + k_i^2(4 + k_j^2) - k_i k_j$.

Having in hand the equilibrium investment levels for all the possible cases, we can now compare them. Proposition 1 presents four key results regarding the role of spillovers for investment incentives.

Proposition 1 *The equilibrium R&D investments satisfy the following:*

- (i) $x_i(0, k) > x_i(0, 0) > x_i(k, 0)$ for all the values of k and γ .
 - (ii) $x_i(k, k) > x_i(k, 0)$ for all the values of k and γ .
 - (iii) $x_i(k, k) > x_i(0, k)$ if γ is sufficiently low and $k > k_1(\gamma)$, with $k_1(\gamma)$ increasing in γ .
- Otherwise, $x_i(k, k) < x_i(0, k)$.

(iv) $x_i(k, k) > x_i(0, 0)$ if γ is sufficiently low for all the values of k and for intermediate values of γ if $k < k_2(\gamma)$, with $k_2(\gamma)$ decreasing in γ . Otherwise, $x_i(k, k) < x_i(0, 0)$.

According to the first inequality of Proposition 1(i), a firm has higher investment incentives in the case that it only receives spillovers than in the case that it neither receives nor sends spillovers. Intuitively, the firm's marginal cost is reduced in the former case due to the incoming spillovers. The decrease in the firm's marginal cost leads to an increase in its output which in turn reinforces the value of any cost reduction, inducing an increase in its R&D investments.¹⁰ In the case instead that the firm only sends spillovers, the outgoing spillovers work in exactly the opposite way than the incoming spillovers, and thus, the firm's equilibrium R&D investments take their lowest value in this case (see Proposition 1(i) and Proposition 1(ii)) This occurs simply because the firm's outgoing spillovers improve the competitive position of its free-riding rival, and thus, they reduce the firm's investment incentives.

Interestingly, a firm's investments can be lower when it only receives spillovers than when it both receives and sends spillovers (see Proposition 1(iii)). In particular, this holds in the area to the left of the $k_1(\gamma)$ curve in Figure 1, that is, when the products are not too close substitutes and the spillovers are high enough. Why is this so? When both firms free-ride on each other's investments, a firm's, e.g. firm 1's, outgoing spillovers have two opposite effects on its investment incentives. First, as mentioned above, firm 1's outgoing spillovers reduce its investment incentives since they improve the competitive position of its rival, firm 2. Second, firm 1's outgoing spillovers constitute firm 2's incoming spillovers, and thus, in accordance with our discussion of Proposition 1(i), they increase firm 2's investments. By the same token, the increase in firm 2's investments leads to an increase in the free-rider's, firm 1's, own investments. When the products are not close substitutes, the first effect weakens since the competition among the two firms is not fierce, and the firm's investments are higher in the presence of outgoing spillovers than in their absence.

It has long been recognized in the R&D literature that spillovers have adverse consequences on investment incentives. Contrary to this and to conventional wisdom, we find that the lack of appropriability can encourage R&D investments. This is suggested by the last part of Proposition

¹⁰For a similar reasoning, in a different context, see Bester and Petrakis (1993), and Milliou (2004).

1, according to which R&D investments can be higher when neither firm protects its investments, that is, in the presence of two-way spillovers, than when both firms protect their investments, and thus, spillovers are absent. This holds in the area to the left of the $k_2(\gamma)$ curve in Figure 1, that is, for any spillovers rate when the products are not too close substitutes and for a sufficient low spillovers rate when the degree of product substitutability takes intermediate values. The intuition behind this result is similar to that of Proposition 1(iii). Since when the products are not too close substitutes both the incoming and the outgoing spillovers reinforce the investment incentives, R&D investments are higher when spillovers are present than when they are absent. Note that the $k_2(\gamma)$ curve is to the right of the $k_1(\gamma)$ curve, and thus, the area where this holds is larger than the respective area where Proposition 1(iii) holds. This is a straightforward implication of the first inequality of Proposition 1(i).

Having explored the impact of spillovers on each firm's R&D investments, one might wonder whether their impact on the "effective" R&D investments, that is, on the total cost reduction due to the R&D investments $x_i(k_i, k_j) + k_j x_j(k_j, k_i)$, is of a similar nature.

Proposition 2 *The effective R&D investments are always higher when both firms do not protect their investments than when both firms protect their investments.*

According to Proposition 2, the presence of spillovers always has a positive impact on the effective R&D investments. The intuition is as follows. When both firms protect their investments, a firm's marginal cost is reduced only by the firm's own R&D investments. When instead both firms do not protect their investments, a firm's marginal cost is reduced both by its own R&D investments and by (a part of) its rival's R&D investments. The additional cost reduction due to the free-riding on the rival's R&D investments in the latter case turns out to be greater than the one due to the (possible) increase in the firm's own investments in the case of protection. As a result, the total cost reduction is higher in the case of no protection than in the case of protection.

4 Protection vs. No Protection

In light of the impact of spillovers on R&D investments, we turn now to the analysis of the firms' decisions regarding the protection of their investments.

It follows from the description of our model that there are three candidate equilibria in the first stage of the game: (1) $[P, P]$ where both firms protect their innovations, i.e. $k_1 = k_2 = 0$; (2) $[NP, NP]$ where neither of the firms protects its innovation, i.e. $k_1 = k_2 = k$; (3) $[P, NP]$ where only one of the firms, firm 1, protects its innovation, i.e. $k_1 = 0$ and $k_2 = k$.¹¹ Proposition 3 includes our main findings.

Proposition 3 (i) $[NP, NP]$ is an equilibrium if γ is sufficiently low and $k > k_3(\gamma)$, with $k_3(\gamma)$ increasing in γ , (ii) $[P, P]$ is an equilibrium for all the values of γ and k , and (iii) $[P, NP]$ is never an equilibrium.

Contrary to conventional wisdom, we find that a firm can prefer being both a receiver and a sender of spillovers to being only a receiver of spillovers. In other words, the case in which the two firms do *not* protect their investments $[NP, NP]$ can arise in equilibrium (see Proposition 3(i)). This actually happens in the area to the left of the $k_3(\gamma)$ in Figure 1, i.e. when the spillovers are high enough and the products are not too close substitutes. Note that in the largest part of this area the R&D investments are also higher in the $[NP, NP]$ case than in the $[P, P]$ case. This is important for the intuition. In particular, the reason that a firm has incentives to let its R&D information flow is in order to enhance the investments of its rival on which it free-rides itself.

From Proposition 3(ii) it follows that $[NP, NP]$ is not the only equilibrium. The case in which both firms choose to protect their investments $[P, P]$ is always an equilibrium when protection is costless. This is quite intuitive. A firm has no incentives to deviate from $[P, P]$ to a situation in which it will be sending spillovers without receiving any $[NP, P]$. Proposition 3(i) and Proposition 3(iii) together imply that under certain conditions we have two equilibria, the $[NP, NP]$ equilibrium and the $[P, P]$ equilibrium. Interestingly, firms are always better off under $[NP, NP]$ than under $[P, P]$. In other words, the $[NP, NP]$ equilibrium is Pareto superior to the $[P, P]$ equilibrium, and thus, it is more likely that firms will choose the $[NP, NP]$ equilibrium. To understand this, recall that the effective R&D investments under no protection from neither firm exceed the respective ones under protection by both firms (Proposition 2). This clearly implies that firms face a lower

¹¹Note that there is another candidate equilibrium, $[NP, P]$. We omit its analysis because it is similar to the analysis of $[P, NP]$.

production cost in the former case. Because the additional reduction that they enjoy under no protection does not (necessarily) arise from higher R&D investment costs, the presence of spillovers has a positive impact on firm's net profits. This finding suggests that firms would benefit by committing *ex-ante* that they will make their R&D investments publicly available. Combined with Proposition 3, it also suggests that when $[NP, NP]$ does not arise in equilibrium, firms are trapped into a prisoners' dilemma situation.

Proposition 4 *Firm's profits are higher in the $[NP, NP]$ case than in the $[P, P]$ case even if protection is costless, $\pi_i(k, k) > \pi_i(0, 0)$.*

Our next goal is to ascertain whether it is socially preferable to have firms protect their innovations. Defining welfare as the sum of consumers' and producers' surplus, we find the following.

Proposition 5 *Welfare is higher in the $[NP, NP]$ case than in the $[P, P]$ case even if protection is costless.*

Proposition 5 establishes that protection leads to a decrease in welfare, even when it comes from free. In view of our previous results, the intuition for the negative impact of protection on welfare is straightforward. Recall that according to Proposition 2, the effective R&D investments are lower under protection. The lower effective R&D investments translate into higher marginal costs that lead, in turn, to an increase in the final prices, and thus, to lower consumers' surplus. Recall also that according to Proposition 4, firm's profits are lower in the absence of any spillovers than in the presence of two-way spillovers. Therefore, both the consumers' and the producers' surplus is lower when firms protect their investments.

Although Proposition 5 indicates that the absence of protection is always preferable from a social point of view, we have seen that firms do not always choose to leave their investments unprotected (Proposition 3). Since an increase in the degree of spillovers rate could lead to the emergence of the $[NP, NP]$ equilibrium (see the area above $k_3(\gamma)$ in Figure 1), Proposition 5 suggests that there is scope for public policy intervention, and in particular, for policy that actively promotes the dissemination of technological knowledge. This could be achieved through policies that facilitate the communication among researchers (financing of conferences etc.) and

the mobility of workers. There is a lively policy debate about the trade secret protection laws and the inclusion of covenants in employment contracts (e.g. "covenants not to compete") that limit workers' mobility. Our findings are clearly against both of these practises.¹²

5 Extensions

In this Section, we extend our model in four directions: the number of competing firms, the cost of protection, the type of competition, and the efficiency of the R&D technology.

5.1 Number of Firms

Next, we consider the n -firm case, with $n > 2$, in order to examine how the number of firms affects our main findings.

The (inverse) demand function faced by firm i , with $i, j = 1, 2, \dots, n$, is now given by:

$$p_i(q_i, Q_{-i}) = a - q_i - \gamma Q_{-i}, \text{ where } Q_{-i} = \sum_{j \neq i} q_j \quad (7)$$

Accordingly, firm i 's profits are:

$$\pi_i(q_i, Q_{-i}, x_i, X_{-i}, n) = p_i(q_i, Q_{-i})q_i - (A - x_i - X_{-i})q_i - x_i^2, \quad (8)$$

where $X_{-i} = \sum_{j \neq i} k_j x_j$. The first order condition of (8) with respect to q_i is:

$$a - 2q_i - \gamma Q_{-i} - A + x_i + \sum_{j \neq i} k_j x_j = 0. \quad (9)$$

Adding up the n first order conditions, we obtain:

$$Q = \frac{n(a - A) + \sum_{i=1} x_i + (n - 1) \sum_{i=1} k_i x_i}{2 + \gamma(n - 1)}, \text{ where } Q = \sum_{i=1} q_i. \quad (10)$$

¹²Kogut and Zander (1995) provide evidence that labor mobility is an important source of spillovers. According to Saxenian (1994) and Almeida and Kogut (1999), there is a high turnover rate of engineers and of highly skilled personnel in general in Silicon Valley (California) that contributes to the diffusion of technological knowledge. Moreover, the employment legislation in the state of California bans "covenants not to compete".

By solving (9), after substituting (10), we can obtain the equilibrium quantities for given levels of R&D investments, $q_i(x_i, X_{-i}, n)$. Using $q_i(x_i, X_{-i}, n)$, firm i 's profits (8) can be rewritten as: $\pi_i(x_i, X_{-i}, n) = [q_i(x_i, X_{-i})]^2 - x_i^2$. Maximizing $\pi_i(x_i, X_{-i}, n)$ with respect to x_i , and exploiting symmetry, we can attain the equilibrium R&D investments. The expression for the equilibrium R&D levels in the symmetric case, i.e. when $k_1 = k_2 = \dots = k_n = \tilde{k}$, is:¹³

$$x_i(\tilde{k}, n) = \frac{(a - A)[2 - \gamma(2 + \tilde{k}(n - 1) - n)]}{6 - 2\tilde{k}(n - 1) + \gamma[(\tilde{k}^2 - \gamma^2)(n - 1)^2 + (2\gamma - \tilde{k})(3 - 4n + n^2) - (10 - 7n)]}.$$

Comparing the R&D investments in the presence of two-way spillovers $x_i(k, n)$ with those in the absence of any spillovers $x_i(0, n)$ for different values of n , we are able to draw two main conclusions. First, we conclude that the last part of Proposition 1 is robust to the number of firms that operate in the market. In particular, $x_i(k, n) > x_i(0, n)$ holds to the left of each of the curves in Figure 2, with each curve corresponding to a different number of firms. Clearly then, the positive effect of spillovers on the investment incentives holds independently of the number of firms. Our second conclusion is that, as long as k is high enough, the area in which the spillovers have a positive effect on investments decreases with n . That is, the more firms exist in the market, the less likely is that spillovers encourage the R&D investments. Exactly the opposite can be stated when the spillovers are sufficiently low. In this case, spillovers can encourage the investments even when the products are close substitutes (high γ) as long as there are many firms in the market. This is illustrated in Figure 2, where one can note that when the number of firms increases, the critical curves shift to the left in the figure's upper part (k high) and to the right in its lower part (k low).

Turning to the analysis of the n firms' incentives to protect their investments, we note that in accordance to our main analysis, there exist conditions under which firms choose to let their R&D information flow to their competitors. This holds to the left of each of the curves in Figure 3, with each of the curves corresponding again to a different number of firms. However, we also note that the more firms exist in the market, the harder is to sustain the equilibrium in which all firms let their R&D information flow. This can be seen in Figure 3, where the critical curves shift to the

¹³By symmetric case, we refer both to the case that all the firms protect their investments and to the case that none of the firms protects its investments. The expressions for the equilibrium investments in the other cases are omitted here because they are quite long. However, they are available from the author upon request.

left as the number of firms increases. The intuition is as follows. Consider a setting in which there are many firms with none of them concealing its R&D investments. If a firm deviates from this setting, then it will have an advantage relative to its competitors. This is so because while it will be free-riding on the investments of $n - 1$ firms, each of the other firms will be free-riding on the investments of $n - 2$ firms. Recall that the main reason that a firm did not always have incentives to deviate was that its outgoing spillovers could affect positively the investments of its competitor. The more firms there are in the market and thus the more are the sources of incoming spillovers, the less important is the role of a single firm's outgoing spillovers in affecting the investing incentives of its competitors, and thus, the stronger are the firm's deviation incentives.

5.2 Protection Cost

We have assumed in our basic model that a firm can protect its investments without incurring any cost. While this could be the case in some instances, in others, the protection measures can be costly. Here, we discuss the robustness of our results in the latter case by assuming that there is a fixed cost of protection K , with $K > 0$.

Under this setting, our findings regarding the R&D investments clearly remain unchanged. However, the firms' incentives to protect their investments as well as the welfare implications of protection are altered. In particular, the incentives of firms to leave their investments unprotected are reinforced. A straightforward implication of this is that the case in which both firms choose to not protect their investments $[NP, NP]$ is an equilibrium for a larger range of parameters. Actually, if K is sufficiently high, $[NP, NP]$ could arise in equilibrium even when the products tend to be homogeneous. At the same time, $[P, P]$ does not continue to always be an equilibrium. There is a critical value of the protection cost \bar{K} , such that $[P, P]$ does not arise in equilibrium when $K > \bar{K}$.

Recall that according to Proposition 4, when protection is costless, welfare is lower when firms protect their investments than when they leave them unprotected. Clearly, this result along with the incentives to promote the sharing of knowledge are now stronger, since protection has an additional drawback, it is costly.

5.3 Bertrand Competition

In our basic model, firms produce differentiated goods and compete in quantities. Here, we consider the case in which firms compete in prices instead.

As demonstrated by Singh and Vives (1984), the demand function (1) faced by firm i can be rewritten in the following way:

$$q_i(p_i, p_j) = \frac{a(1-\gamma)}{1-\gamma^2} - \frac{1}{1-\gamma^2}p_i + \frac{\gamma}{1-\gamma^2}p_j.$$

Using the above demand function and assuming that in the last stage of the game firms choose simultaneously and independently their prices, we are able to confirm all the qualitative results of our basic model.¹⁴ We are also able to note that the areas in which Proposition 1(iv) and Proposition 3(i) hold are smaller under Bertrand competition than under Cournot competition. This occurs because, as it is well-known, competition in the former case is stronger.

5.4 Cost of R&D Investments

Throughout our analysis we have assumed that the cost of the R&D investments is given by x_i^2 . Here, we explore the role of the efficiency of the R&D technology for our findings by considering the case that the R&D investments' cost is given by $\mu x_i^2/2$, with $\mu > 0$.¹⁵ Clearly, the parameter μ captures the efficiency of the R&D technology. Namely, a higher μ reflects a lower efficiency of the R&D investments.

Doing so, we confirm our main finding regarding the R&D investments. Moreover, we find that the critical value $k_2(\gamma, \mu)$ (with $k_2(\gamma, 2) = k_2(\gamma)$) for the investments in the $[NP, NP]$ case to exceed those in the $[P, P]$ case, is decreasing in μ . Hence, the more efficient is the R&D technology (lower μ), the more likely is that the presence of spillovers leads to an increase in the R&D investments. Recall that a firm's incoming spillovers were reinforcing the firm's R&D investment incentives because they were improving its R&D productivity. Clearly, the more efficient is a firm's R&D technology, the more advantage it can take of the improvement in the marginal benefit of its R&D

¹⁴The analysis is available from the author upon request.

¹⁵In order for the second order conditions to hold we need to assume that $\mu > 4/[(2-\gamma)^2(2+\gamma)]$. The value of $\mu = 2$ that we used in our main analysis clearly satisfies this assumption.

efforts. An implication of this is that Proposition 1(iv) holds for higher values of the degree of product substitutability γ when μ takes smaller values. Similarly, through numerical calculations, we can conclude that the more efficient is the R&D technology, the higher is the area in which firms choose to leave their investments unprotected (Proposition 3(i)). These findings suggest that R&D subsidies, that lead to a decrease in the cost of R&D investments, could stimulate the diffusion of R&D knowledge, and thus, they could have a welfare enhancing effect.

6 Concluding Remarks

In this paper, we have explored the incentives of firms to protect their non-cooperative investments from flowing to their competitors. We have also asked whether or not public policy should induce firms to protect their investments. We have departed from the existing literature by considering a setting in which firms can influence the appropriability of their innovation without necessarily affecting the appropriability of their competitor's innovation.

We have shown that, under some circumstances, firms decide to not protect their R&D investments even when their protection is costless. Firms have incentives to let their R&D information flow in order to enhance the investments of their rivals on which they free-ride in turn. Clearly, this finding suggests that, in contrast to conventional wisdom, the commonly observed technological spillovers are not necessary involuntary.

Interestingly, when the firms do not leave their investments unprotected, they are trapped into a prisoners' dilemma situation. The prisoners' dilemma arises because firms are better off when none of them protects its investments than when both of them protect them. Moreover, consumers are also better off when firms do not protect their investments. This occurs because the total cost reduction enjoyed by firms is higher when they can free-ride on each other's investments than the respective one in the absence of any free-riding. The negative impact of protection on both producers' and consumers' surplus indicates that policy makers should not promote trade secret protection and employment legislation that discourages workers' mobility. Instead, they should adopt policies that facilitate the creation of open research environments, the communication of researchers and the mobility of workers.

We have assumed throughout that a firm can fully protect its investments, that is, when a firm decides to protect its investments its outgoing spillovers are equal to zero. The obvious next step is to extend the analysis to a setting in which the level of protection is endogenous. This could be achieved by introducing investments in protection and assuming that the higher are the firm's investments in protection, the lower are its outgoing spillovers. We conjecture that in this setting firms would again choose to not fully protect their investments not only for the reasons that we have identified in the present paper but also because full protection would be more costly. The formal analysis under this setting is more complicated and awaits future research.

7 Appendix

Proof of Proposition 1: (i) It follows immediately after taking the difference $x_i(0, k) - x_i(0, 0)$ as well as the difference $x_i(0, 0) - x_i(k, 0)$.

(ii) We take the difference $x_i(k, k) - x_i(k, 0)$ and we note that it is always positive.

(iii) We take the difference $x_i(k, k) - x_i(0, k) = M_1(\gamma, k)$. Clearly, $\lim_{k \rightarrow 0} M_1 = 0$. It can be checked that $M_1(\gamma, 1) = 0$ when $\gamma = 0.111$. It can also be checked that $M_1(0, k) > 0$ and $\lim_{\gamma \rightarrow 1} M_1 < 0$ for all the values of k and that $\frac{\partial M_1}{\partial \gamma} < 0$. Thus, there exists a critical value $k_1(\gamma)$, such that $M_1(\gamma, k) > 0$ if γ is sufficiently low and $k > k_1(\gamma)$ with $\frac{\partial k_1}{\partial \gamma} > 0$. Otherwise, $M_1(\gamma, k) < 0$.

(iv) We take the difference $x_i(k, k) - x_i(0, 0) = \frac{k(a-A)N_1(\gamma, k)}{D_1}$, where $N_1(\gamma, k) = 4 - \gamma^2(4 - 2\gamma - \gamma^2) - 2\gamma(4 + k)$ and $D_1(\gamma, k) = [6 + \gamma(4 - 2\gamma - \gamma^2)][2(3 - k) - \gamma^2(2 + \gamma) + \gamma(4 + k + k^2)] > 0$. It is easy to check that $\lim_{k \rightarrow 0} N_1 > 0$ and $N_1(\gamma, 1) = 0$ when $\gamma = 0.359$. Setting $N_1(\gamma, k) = 0$ and solving for k we obtain: $k_2(\gamma) = \frac{4 - \gamma[8 + 2\gamma(2 - \gamma) - \gamma^3]}{2\gamma}$, with $\frac{\partial k_2}{\partial \gamma} < 0$. It follows that $N_1(\gamma, k) > 0$ if γ is sufficiently low and $k < k_2(\gamma)$. Otherwise, $N_1(\gamma, k) < 0$. ■

Proof of Proposition 2: Firm i 's effective R&D investments are given by $x_i(k_i, k_j) + k_j x_j(k_j, k_i)$. It follows that in the case that neither firm protects its investments they are equal to $(1 + k)x_i(k, k)$. In the case instead that both firms protect their investments, firm i 's effective R&D investments are equal to $x_i(0, 0)$. After taking the difference $(1 + k)x_i(k, k) - x_i(0, 0)$ one can easily note that it is always positive. ■

Proof of Proposition 3: (i) It is sufficient to show that firm 1's profits under $[NP, NP]$ are

higher than those under $[P, NP]$. Taking the difference $\pi_1(k, k) - \pi_1(0, k) = M_2(\gamma, k)$. We know that $\lim_{k \rightarrow 0} M_2 = 0$. It can be checked that $M_2(\gamma, 1) = 0$ when $\gamma = 0.39$. Moreover, it can be checked that $M_2(0, k) > 0$ and $\lim_{\gamma \rightarrow 1} M_2 < 0$ for all the values of k and that $\frac{\partial M_2}{\partial \gamma} < 0$. Thus, there exists a critical value $k_3(\gamma)$, that we can find by setting $M_2(\gamma, k) = 0$, such that $M_2(\gamma, k) > 0$ if γ is sufficiently low and $k > k_3(\gamma)$ with $\frac{\partial k_3}{\partial \gamma} > 0$. Otherwise, $M_2(\gamma, k) < 0$.

(ii) One can easily check that $\pi_1(0, 0) - \pi_1(k, 0) > 0$.

(iii) It follows immediately from part (ii). ■

Proof of Proposition 4: It follows immediately after taking the difference $\pi_i(k, k) - \pi_i(0, 0)$. ■

Proof of Proposition 5: Total welfare is given by:

$$W(k_i, k_j) = (a - A)(q_i^* + q_j^*) - \frac{1}{2}[(q_i^*)^2 + (q_j^*)^2 + 2\gamma q_i^* q_j^*] \\ + (x_i^* + k_j x_j^*)q_i^* + (x_j^* + k_i x_i^*)q_j^* - (x_i^*)^2 - (x_j^*)^2,$$

where $q_i^* = q_i(k_i, k_j)$ and $x_i^* = x_i(k_i, k_j)$. We take the difference $W(k, k) - W(0, 0)$ and we note that it is always positive. ■

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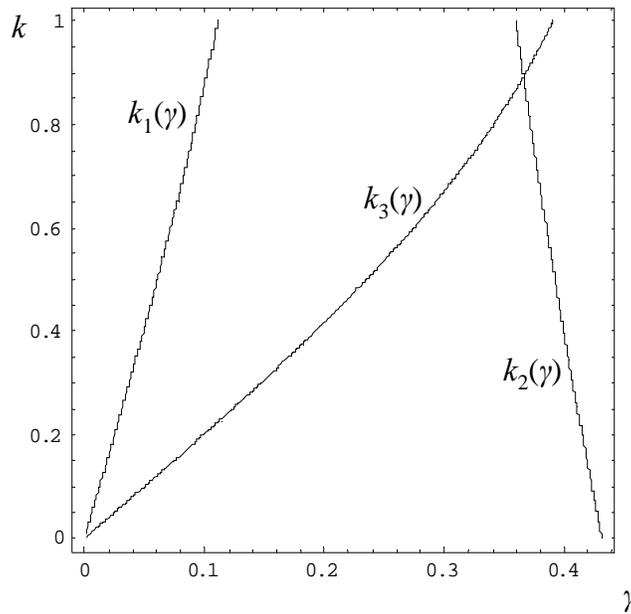


Figure 1: R&D Comparison and Equilibrium with 2 Firms

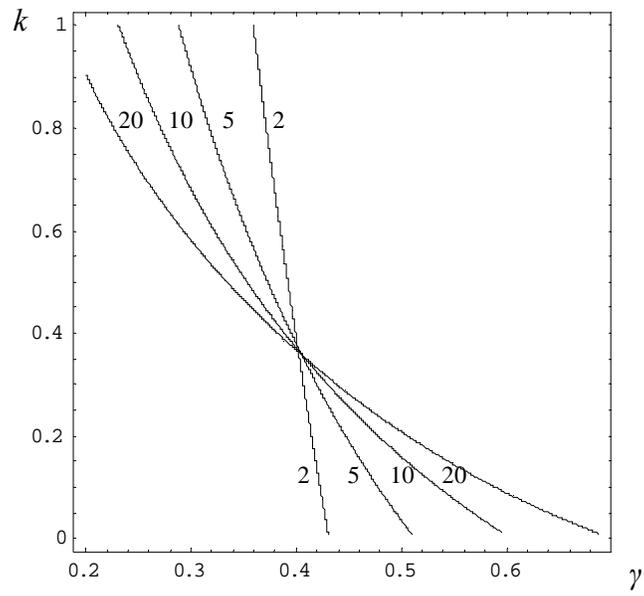


Figure 2: R&D Comparison with n firms

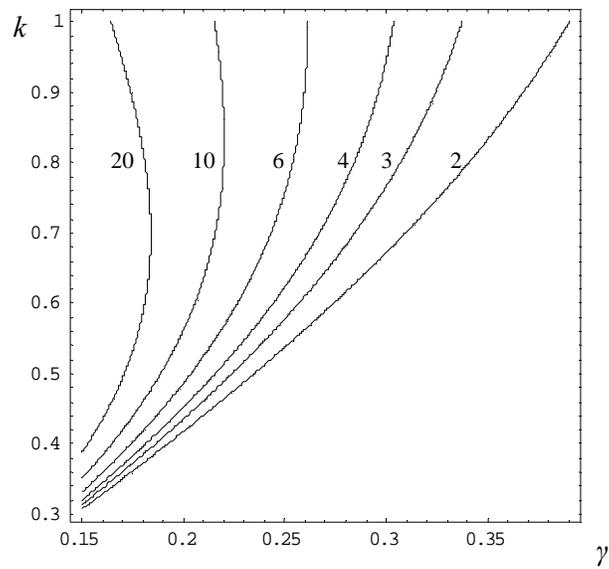


Figure 3: Equilibrium with n firms