Spillovers and R&D Incentive under Incomplete Information

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Abstract

Spillovers of R&D outcome affect the R&D decision of a firm. The present paper discusses R&D incentives when the extent of R&D spillover is private information to every receiving firm. We concentrate on a two stage game involving two firms when the firms first decide simultaneously whether to invest in R&D or not, then they compete in quantity. Assuming general distribution function of firm types we compare R&D incentives of firms under alternative scenarios based on different informational structures. The paper shows that R&D incentives can be larger with spillovers under incomplete information.

Keywords: R&D incentives, Cournot duopoly, Spillovers, Asymmetric information.

JEL Classification: D43, D82, L13, O31.

1 Introduction

Spillovers of R&D results are common phenomena in industries. Spillover, in most general terms, depicts a situation where there is intentional or unintentional leakage of the R&D results of a firm to other firms in within or across industries. There is a large literature to show that the possibility of knowledge spillovers affects the R&D decisions of a firm. In presence of spillovers, firms tend to underinvest in R&D (see for instance Katz (1986), d'Aspremont and Jacquemin (1988), Kamien et.al. (1992), and Suzumura (1992)). Perhaps that is why firms get very often involved in race for winning patents in order to secure their R&D output. Patent race is also widely studied in the R&D literature (e.g. Shapiro (1985), Baye and Hoppe (2003), Baker and Mezetti (2005) etc.).

However, it may not always be possible to get patent for every innovation. Also an innovation has to pass through multiple rounds of examination so as to ascertain that the innovation is indeed an original one and it does not have "substantial" overlapping with any prior patented innovation[1]. Thus even if it is possible to obtain a patent,getting a patent involves time. If obtaining a patent takes a longer bit of time, then by the time the patent is obtained, it may not serve the purpose of protecting the benefits of the innovation as other competing innovations may have come into being in the mean time. Another important fact is that even when patents are available they are imperfectly enforced and even when a patent is infringed, proving the case is a lengthy process. Therefore, when patents are either not available or are not effective enough to prevent appropriation of R&D benefits by other firms, incentives of an innovating firm to undertake R&D activities decline, and hence firms tend to underinvest in R&D both from industry and social point of view (Conti (2014)). Ornaghi (2006) has drawn attention to the existence of a possible gap between private and social rates of return of R&D; this reflects insufficient appropriability from R&D investments. That a firm benefits from R&D of their rivals is also evident in Jaffe (1986) which provides empirical evidence of the presence of spillovers.

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[1] How much overlapping allowed in case of issuing a fresh patent may vary from country to country or situation to situation

To further motivate the problem of non-appropriability of R&D knowledge in the presence of spillovers consider Research Joint Ventures (RJVs). As shown by d'Aspremont and Jacquemin (1988), RJV enhances the level of R&D investment when spillovers are high. That is why in some countries the governments provide incentives for RJVs for corporate research in general by giving direct subsidy, tax credit, and infrastructural support. As noted by Ghosh and Ghosh (2014), to promote RJVs among firms in the US, the National Cooperative Research Act was designed. However, it is not always possible to have RJVs because of moral hazard or other problems. Since RJVs may also lead to market concentration, at times they are prevented by anti-trust laws. Sometimes firms themselves may feel discouraged to enter RJVs since the resulting innovation keeps both the firms on equal footage thus not providing enough competitive edge to firms over their rivals. Conti (2014), in particular, observes that due to asymmetries among firms, especially in terms of their sizes, the benefits of RJVs may be distributed unevenly which is likely to create disincentives for collaboration among firms.

Now, given that there are spillovers, different firms may have different absorptive capacities depending on their size, past experiences and adapting capabilities. (Kought and Zander (1992)). This in turn determines the extent of spillovers of an innovation to be enjoyed by a firm. However, these absorptive capacities, determined endogenously can very well be privately known to the concerned firms. How much spillovers would occur for an innovation is likely to be a variable determining investment of an R&D firm. Thus in the presence of spillovers firms decide whether to invest in R&D or not depending on what information they have about their rivals' abilities of benefiting from spillovers of their R&D knowledge. Therefore this paper makes an attempt to study the R&D incentive of a firm in a duopoly under different information scenarios where spillover of R&D knowledge is involuntary and automatic. We term the proportion of the R&D output that gets spilled over to a firm from its rival firm is its spillover parameter. Each firm in our framework is always aware of its own spillover parameter, but it may or may not know the spillover parameter of its rival since the ability to benefit from spillover of knowledge from other sources depends largely on endogenous factors of a firm and these factors may not be observable to outsiders. Accordingly, we are in regime of complete information. When every firm knows its own as well as its rival's spillover parameters, we have a complete information framework. When a firm can only observe its own spillover parameter but not of the rival's, we are in an incomplete information scenario. In case of incomplete information, thus, the spillover parameters constitute types of the firms. This paper considers general distribution function of firm types.

Impact of spillovers on R&D incentives in a complete information framework is quite well looked at in the literature. Reinganum (1981) shows how if "the value of adopting a cost-reducing, capital embodied process innovation declines with the number of firms"; then the adopting firms are induced to use newer technologies in a sequence and thus the knowledge gets diffused over time. Grilliches (1992) emphasises the importance of R&D spillovers with supportive empirical evidence. Mookherjee and Ray (1991) considers the diffusion of the latest technology developed by a dominant firm to competitive fringe firms for both price and quantity competition in the product market. In their model, Schumpetrian cycles of innovation and diffusion are observed in the product market when there is price competition. Their result shows that an increase in the rate of diffusion enhances the pace of innovation up to a certain point and has ambiguous effect on R&D incentives for price competition and the results are reversed for quantity competition. Harhoff (1991) elaborates a scenario involving a monopoly supplier of intermediate goods to an oligopoly industry, where the monopoly supplier deliberately allows spillover of its R&D output which substitutes the R&D efforts of the competing firms in the oligopoly industry. This leads to an expansion in the output of oligopoly industry thus raising the demand for the input supplied by the monopoly firm and this is how the monopoly firm benefits indirectly despite the absence of a market for R&D information. De Bondt (1997) explains how spillover possibilities discourage R&D due to free riding by rivals. However, De Bondt (1997) also discusses how spillover can create incentives for R&D as R&D efforts by one firm induces other firms to undertake similar endeavours and thus all of them end up producing at lower costs leading to lower prices and therefore enhanced demand, which De Bondt (1997) formally calls "market expansion effect". R&D

incentives in upstream downstream industry structure is studied in Kabiraj and modak (2016).

R&D incentives are also impacted on by prevailing market structures. De Bondt (1997) notes that R&D incentives are higher in oligopolistic market structures compared to both the the extremes of perfect competition and monopoly. Matsumura et. al. (2013) consider a duopoly industry and find a non-monotone relationship between degree of competitiveness and R&D investment. Shibata (2014) extends the work of Matsumara et.al. (2013) by incorporating the possibility of R&D spillovers. The results show that for duopoly markets, non-cooperative R&D is preferred over cooperative R&D when spillovers are small (less than half), but for large spillovers (i.e. more than half) cooperative R&D is the more preferred mode.

R&D incentives under incomplete information is relatively a less trodden area. However, there are a few interesting works. Conti (2014) investigates the role of asymmetric information in context of RJVs in a duopoly market in presence of spillovers. It considers a situation where firms are symmetric initially, but they differ in terms of their R&D abilities leading to inter-firm asymmetry after the R&D. This paper however deals with one sided asymmetry, i.e. only one firm has private information about its R&D ability. The paper by Frick et.al. (2016) studies a duopoly market where firms decide both R&D investment levels and entry time i.e. when to introduce the new product in the market in an incomplete information framework. Here, both the firms try to develop a prototype, and once it is developed, they decide when to introduce the new product. The firms differ in terms of their R&D abilities and thus the earliest date at which a prototype can be created varies across firms. This earliest date is private information to every firm. Whichever firm succeeds in developing the prototype first takes away the whole profit. Observability of the rival's R&D activity plays no role in the decision regarding R&D investment in this model. In a recent paper Chatterjee et.al. (2017) have studied R&D incentive of a firm under both sided asymmetry, but with no spillover. The present paper is an extension of this paper where there is spillover of R&D results, but the extent of R&D spillover is private information.

Existence of spillovers generally reduce R&D incentives in a complete information framework as noted earlier. But under incomplete information, R&D incentives may go up under certain situations. R&D incentives when spillover parameters are private information have not been explored so far. This paper makes an attempt to fill this gap in the literature by addressing this issue in a quite general framework.

The organisation of the paper is as follows. Section 2 discusses the model setup. sections 3 and 4 elaborate the complete information scenario in absence and presence of R&D spillovers respectively, section 5 elaborates on the incomplete information scenario, section 6 compares the threshold values of the spillover parameter under alternative information scenarios and section 7 concludes the paper.

2 Model Setup

We consider a Cournot duopoly. The firms are denoted by A and B. The inverse demand function of the market is given by $P = \max\{0, a - Q\}$, where $a > 0$ and Q is the aggregate output produced in the market. Firms have constant and positive marginal cost denoted by c.

Firms are deciding to invest in a cost reducing R&D. The cost of the R&D is H which is positive and is assumed to be equal for both the firms. If a firm undertakes the R&D then her marginal cost becomes $c - D$, where $0 < D < c$. We further assume $a > c + D$.

Suppose firm j invests in R&D but firm i does not; then a part of the R&D will diffused to firm i. The amount of spillover is denoted by d_i. So the marginal cost of firm i after the spillover is $c - d_i$. Clearly $d_i \in [0, D]$ for all $i \in \{A, B\}$. We assume that d_i is distributed with the distribution function $F(\cdot)$ and continuous density function $f(\cdot)$ and has full support. Therefore, d_i also denotes the type of firm i and is private information to firm i in case of incomplete information. It is assumed that firm i knows its own type, before deciding on the R&D activity.

Some notations: $W := a - c$, $q(x) := \frac{W+x}{3}$, $\Pi(x) := q^2(x)$ and $\Psi(x) := \int_x^D y \frac{dF(y)}{1-F(x)}$[2]. Note that $q' > 0$, $\Pi'(x) = \frac{2}{3}q(x) > 0$, $\lim_{x \to D} \Psi(x) = D$ [3] and $\Psi'(x) > 0$ when $x \in (0, D)$.

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[2] The average value of y given that y lies between x and D.

[3] The intuition is that $\Psi(x)$ must lie between x and D.

Denote 'doing research' by R and 'no research' by N. Suppose firm A chooses to invest in research and firm B does not, then we denote profit (expected profit) of the firm A by $\Pi_A^{[RN]}$ ($E\Pi_A^{[RN]}$) and that of firm B by $\Pi_B^{[RN]}$ ($E\Pi_B^{[RN]}$). Similar notation will be used for other cases.

Our objective is to find out how the decision of performing the research is dependent on the type of a firm and the level of information available to it. So it is a two stage game. In the first stage each of the firms is deciding whether to invest in research. And in the second stage they are competing in the after-market.

3 Complete information: No Spillover

If a firm invests in research then its marginal cost is $c - D$, otherwise it is c.

Lemma 1. *The following statements hold:*

- *If none of the firms invests in research then each one has a profit of* $\Pi(0)$.
- *If both of them invest in research then each one has a profit of* $\Pi(D) - H$.
- *If firm i invests in research and firm j does not then the profit of firm i is* $\Pi(2D) - H$ *and the profit of firm j is* $\Pi(-D)$.

From the results in the above lemma , we find that if the rival is not doing research then it is always optimal for firm i to do research if and only if $\Pi(2D) \geq \Pi(0) + H$, that is, if and only if $\frac{4(W+D)D}{9} \geq H$. Second, if the rival firm is doing the research then the firm i will do the research if and only if $\Pi(D) \geq \Pi(-D) + H$, that is, if and only if $\frac{4WD}{9} \geq H$.

Proposition 1. *The following statements hold:*

- *Both of them will invest in research if* $\frac{4WD}{9} \geq H$.
- *None of the will invest in research if* $\frac{4D(W+D)}{9} \leq H$.
- *Only one of them will invest in research if* $\frac{4WD}{9} < H < \frac{4D(W+D)}{9}$.[4]

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[4] The model does not predict which of the firms will invest in research in this scenario.

4 Complete Information: With Spillover

We assume in this section that everything is common knowledge, including the types of the firms. Since we are considering duopoly, at equilibrium three cases can happen: (1) both the firms invest in R&D, (2) none of the firms invests in R&D and (3) one firm invests and the other does not. The lemma below summarizes the payoffs of a firm under different equilibrium situations.

Lemma 2. *Given two firms i and j, $i = A, B$, $j = A, B$ and $i \neq j$,*

a. *If both of them have not invested in research then each of them gets* $\Pi_i^{[NN]} = \Pi_j^{[NN]} = \Pi(0)$

b. *If both of them have invested in research then they both get* $\Pi_i^{[RR]} = \Pi(D) - H$

c. *Suppose firm i does the research and firm j does not, then,* $\Pi_i^{[RN]} = \Pi(2D - d_j) - H$ *and* $\Pi_j^{[RN]} = \Pi(2d_j - D)$

From above, first note that if the rival is not doing research then it is always optimal for firm i to do research if and only if $\Pi(2D - d_j) \geq \Pi(0) + H$, that is if and only if $d_j \leq 2D - \left(\sqrt{W^2 + 9H} - W\right)$.[5] Second, if the rival firm is doing the research then the firm i will do the research if and only if $\Pi(D) \geq \Pi(2d_i - D) + H$ that is if and only if $d_i \leq \frac{\sqrt{(W-D)^2 + (4WD - 9H)} - (W-D)}{2}$.[6] So a firm will definitely invest in research if and only if magnitude of spillover for both the firms is "sufficiently" small.

Note that if $H > \frac{4WD}{9}$ then both of the firms will never do research simultaneously. In this case either none of them will invest in research or only one of them will invest in research[7]. In particular if $H \geq \frac{4(W+D)D}{9}$ then none of them will invest in research.

The comparison of the complete information with and without spillovers reveals that spillover educes incentives to perform R&D as stated in the following proposition.

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[5] The intution is that if the type of the rival is "sufficiently" small then by doing research the firm will earn higher profit, since the spillover effect is small.

[6] If the type of the firm is "sufficiently" small then it is better for the firm to invest in research, since the spillover effect is small.

[7] Our model does not predict which one of the firms will invest in research in this particular case.

Proposition 2. *R&D incentives are lower under spillovers in complete information framework.*

5 Incomplete Information

In this section we consider the incomplete information problem, hence we assume that d_i is private information to firm i. Note that each firm knows its type before it is deciding on R&D investment. Since R&D decision is taken at the first stage, therefore, at the beginning of the production stage, each firm knows whether its rival has has invested in R&D or not. Suppose δ is the threshold value such that a firm will invest in research if and only if its type is less than or equal to δ. Given the cost of the research (i.e. H), our primary objective in this section is to find out δ.

Like the case of complete information we start our analysis by finding out the (expected) payoffs of firms under different situations. The following lemma derives the (expected) profits.

Lemma 3.

- *If both of them have not invested in research then each of them gets*

$$\Pi_A^{[NN]} = \Pi_B^{[NN]} = \Pi(0)$$

- *If both of them have invested in research then they both get*

$$\Pi_i^{[RR]} = \Pi(D) - H$$

- *Suppose firm A does the research and firm B does not.*

$$\Pi_A^{[RN]} = \Pi(2D - \Psi(\delta)) - H$$

and

$$\Pi_B^{[RN]} = \Pi\left(\frac{3d_B + \Psi(\delta)}{2} - D\right)$$

Proof. The expected profit of firm A is given by

$$(K+D)q_A - q_A^2 - q_A \int_\delta^D \frac{q_B(y)dF(y)}{1-F(\delta)}$$

and that of firm B is

$$(K+d_B)\, q_B - q_B^2 - q_B q_A$$

The corresponding reaction functions are

$$(K+D) - 2q_A - \int_\delta^D \frac{q_B(y)dF(y)}{1-F(\delta)} = 0$$

and

$$(K+d_B) - 2q_B - q_A = 0$$

Solving the two reaction functions stated above we get

$$q_A = q\,(2D - \Psi(\delta))$$

and

$$q_B = q\left(\frac{3d_B + \Psi(\delta)}{2} - D\right)$$

The rest of the proof is trivial. □

If firm i is doing research and it does not know whether firm j is doing research or not, then its expected profit is

$$(1-F(\delta))\Pi(2D - \Psi(\delta)) + F(\delta)\Pi(D) - H$$

On the other hand if firm i is not doing research and it does not know whether firm j is doing research or not, then its expected profit is

$$(1-F(\delta))\Pi(0) + F(\delta)\Pi\left(\frac{3d_i + \Psi(\delta)}{2} - D\right)$$

Let $T(x;\delta)$ denote the gross opportunity gain from doing research when the type of the firm is x. Then $T(x;\delta)$ can be defined as

$$T\left(x;\delta\right) := \left(1-F(\delta)\right)\left[\Pi(2D-\Psi\left(\delta\right))-\Pi(0)\right]+F(\delta)\left[\Pi(D)-\Pi\left(\frac{3x+\Psi\left(\delta\right)}{2}-D\right)\right]$$

.

Note that $T(x;\delta)$ is decreasing in x. Also,

$$T(0;0)=\Pi(2D-\Psi(0))-\Pi(0)$$

and with slight abuse of notation let

$$T(D;D) := \lim_{x\to D} T(x;x)=0$$

So $T(0;0) > T(D;D)$. Finally, δ must satisfy the following equation

$$T(\delta;\delta)=H$$

As stated above our objective is to find out δ as a function of H. However, note that till now there is nothing that tells us that for a particular H there will be a unique δ. The following lemma ensures the uniqueness.

Lemma 4. *$T(x;x)$ is strictly decreasing in $(0,D)$.*

Proof. See Appendix A. ☐

The following proposition states the conditions for pooling and separating equilibria.

Proposition 3. *The following inequalities hold:*

- *If $H \leq T(D;D)$ then all the firms will invest in research*
- *If $H \geq T(0;0)$ then no firm will invest in research*

- *Finally, when $T(D;D) < H < T(0;0)$, there exists a unique δ such that a firm will invest in research if and only if its type is less than or equal to δ when δ can be obtained by solving the equality $T(\delta;\delta) = H$.* [8]

The uniqueness of δ given H in the third result is straight from the above lemma.

Since, in the second stage firms are informed about the R&D decision of the rival, this information acts as a signal. So, it is important now to check the incentive compatibility. We claim above that a firm will invest in R&D if and only if the type of the firm is less than or equal to δ. Suppose firm A follows this strategy and believes firm B to be also following the same strategy. Firm B knows firms A's strategy and belief. We can have the following observations as stated in the remarks below.

Remark. Suppose firm B's type is greater than δ but it decides to invest in R&D. Here from the second stage onwards firm A believes that the type of the firm B is less than δ. So, firm A will produce accordingly.

So the expected profit of firm B is

$$(1 - F(\delta))\Pi(2D - \Psi(\delta)) + F(\delta)\Pi(D) - H$$

However, if it had not invested, then its expected profit would have been

$$(1 - F(\delta))\Pi(0) + F(\delta)\Pi\left(\frac{3d_B + \Psi(\delta)}{2} - D\right)$$

From the definition of δ and since $T(x;\delta)$ is strictly decreasing in x, we know that for all $d_B > \delta$ the following holds:

$$\left[(1 - F(\delta))\Pi(0) + F(\delta)\Pi\left(\frac{3d_B + \Psi(\delta)}{2} - D\right)\right] > [(1 - F(\delta))\Pi(2D - \Psi(\delta)) + F(\delta)\Pi(D) - H]$$

So, if firm B's type is greater than δ, then given firm A's strategy and belief, it will never invest in research.

Remark. Suppose firm B's type is less than or equal to δ but it decides not to invest in

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[8] Note that the value of δ depends on the value of H.

R&D. Here from the second stage onwards firm A believes that the type of the firm B is greater than δ. So, firm A will produce accordingly.

So the expected profit of firm B is

$$(1-F(\delta))\Pi(0)+F(\delta)\Pi\left(\frac{3d_B+\Psi(\delta)}{2}-D\right)$$

However, if it had invested then its expected profit would have been

$$(1-F(\delta))\Pi(2D-\Psi(\delta))+F(\delta)\Pi(D)-H$$

Again from the definition of δ and since $T(x;\delta)$ is strictly decreasing in x, we know that for all $d_B \leq \delta$ the following holds:

$$[(1-F(\delta))\Pi(2D-\Psi(\delta))+F(\delta)\Pi(D)-H] \geq \left[(1-F(\delta))\Pi(0)+F(\delta)\Pi\left(\frac{3d_B+\Psi(\delta)}{2}-D\right)\right]$$

So, if firm B's type is less than or equal to δ then, given firm A's strategy and belief, it will always invest in research.

By optimal strategy under incomplete information we mean that the firm will invest in R&D if and only if the type is less than or equal to δ and believes that the rival is following the same strategy. The above two remarks show that given that the rival is following the optimal strategy mentioned above, it is always optimal for a firm to follow the same strategy. So, both the firms following this strategy is a perfect Bayesian Nash equilibrium.

Below we illustrate our findings with an example.

Example 1. Let us assume $a = 10$, $c = 2$, $D = 1$ and $H = 2$. Also assume d_i's are distributed uniformly. So, $W = 8$, $f(x) = 1$, $F(x) = x$, $\Psi(x) = \frac{1+x}{2}$. We have $\Pi(0) = \frac{64}{9}$, $\Pi(D) = 9$, $\Pi(2d_i - D) = \frac{\left(7+\frac{7d_i+1}{4}\right)^2}{9}$ and $\Pi(2D - d_i) = \frac{\left(10-\frac{1+d_i}{2}\right)^2}{9}$. Firm i is indifferent between investing and not investing in research iff

$$(1-d_i)\left[\left(10-\frac{1+d_i}{2}\right)^2-64\right]+d_i\left[81-\left(7+\frac{7d_i+1}{4}\right)^2\right]=18$$

holds. Therefore, $\delta \approx 0.5107$. If research cost is more than 2.917 then no firm will invest in research. On the other hand if there is no research cost then both the firms will always invest in research.

6 Comparison of Threshold Values

To compare the results under incomplete information and complete information, we basically need to compare the threshold values under these two situations. It is important to note that in case of complete information the threshold value depends on the type of the rival firm, whereas in case of incomplete information it does not. So to compare we must first fix the type of the rival firm.

We consider the following two examples.

Example 2. Suppose d_is are distributed with the distribution function d_i^2 over the interval $[0, 1]$, i.e. $D = 1$. Let $a = 10$ and $c = 2$, so $K = 8$. Let $H = 2.3$, so $\delta \approx 0.4238$. Assume $d_B = 0.9$ and $d_A = 0.41$. Clearly, firm A will invest in research in case of incomplete information. However in case of complete information irrespective of whether the other firm is investing in research or not firm A will never invest in research.

Example 3. Suppose d_is are distributed with the distribution function d_i^2 over the interval $[0, 1]$, i.e. $D = 1$. Let $a = 10$ and $c = 2$, so $K = 8$. Let $H = 2.43$, so $\delta \approx 0.3213$. Assume $d_B = \Psi(\delta)$ and $d_A = 0.33$. Clearly, firm A will not invest in research in case of incomplete information. However in case of complete information irrespective of whether the other firm is investing in research or not firm A will always invest in research.

From these two examples it is quite clear that under certain situations incomplete information may create incentives for R&D when there are spillovers of R&D results. The following proposition summarises this finding.

Proposition 4. *There may be situations when spillovers are present, under incomplete information R&D incentives are higher compared to complete information.*

7 Conclusion

This paper considers a two stage game where two firms have to decide whether to invest in R&D or not in the first stage and compete in quantities in a duopoly market in the second stage. If a firm invests in R&D, it experiences lower marginal cost. Even if a firm does not invest in R&D, it can still experience some reduction in its marginal cost due to spillover from the R&D of its rival. The spillover parameter of a firm decides how much spillover benefits it can enjoy from its rival's R&D. However, if both the firms invest in R&D then there is no additional benefit due to such spillover of R&D knowledge. In presence of the type of involuntary and automatic spillover of R&D outputs as considered here, every firm gets to learn whether its rival has performed R&D when the concerned firm does not itself conduct R&D. When the firms are aware of each other's spillover parameters, we are in a complete information framework. However, if no firm can observe the spillover parameter of its rival, we are in the world of incomplete information. Here the spillover parameters constitute types and we consider general distribution of types.

Our results show that whether under complete information the firms will invest more in R&D as compared to the situation of incomplete information, cannot be stated unambiguously. The parametric values for which spillovers encourage R&D investments support De Bondt's (1997) analysis and our result is thus a generalisation of the incentive creating effects of spillovers in an incomplete information framework.

Here we have considered success to be a definite outcome of R&D. However, there might be associated uncertainties that might be incorporated in the framework of the model. Further research can be done in this direction to identify the conditions for higher R&D incentives for firms in presence of spillover as well as uncertainties in R&D under various information structures.

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A Proof of Proposition 4

$$\begin{aligned}
9T(x;x) &= (1-F(x))[K^2+2K(2D-\Psi(x))+(2D-\Psi(x))^2-K^2] \\
&\quad + F(x)\left[K^2+2KD+D^2-K^2-2K\left(\frac{3x+\Psi\left(x\right)}{2}-D\right)-\left(\frac{3x+\Psi\left(x\right)}{2}-D\right)^2\right] \\
&= (1-F(x))[2K(2D-\Psi(x))+(2D-\Psi(x))^2] \\
&\quad + F(x)\left[2KD+D^2-2K\left(\frac{3x+\Psi\left(x\right)}{2}-D\right)-\left(\frac{3x+\Psi\left(x\right)}{2}-D\right)^2\right] \\
&= 2K(2D-\Psi(x))+(1-F(x))(2D-\Psi(x))^2 \\
&\quad + F(x)\left[D^2+2K\Psi(x)-2KD-2K\left(\frac{3x+\Psi\left(x\right)}{2}-D\right)-\left(\frac{3x+\Psi\left(x\right)}{2}-D\right)^2\right] \\
&= 2KD+D^2-F(x)\left[2K\left(\frac{3x+\Psi\left(x\right)}{2}-D\right)+\left(\frac{3x+\Psi\left(x\right)}{2}-D\right)^2\right] \\
&\quad + 2K(D-\Psi(x))(1-F(x))+(1-F(x))[2D(D-\Psi(x))+(D-\Psi(x))^2]
\end{aligned}$$

Now it can be easily seen that $\frac{d}{dx}9T(x;x) < 0$. This completes the proof.