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Abstract

We study the incentives for firms to share knowledge when they engage in R&D in order to make an uncertain innovation. The initial stock of knowledge may be unevely distributed, and we look at how this affects the type of cooperative agreements that the firms will find it profitable to enter in to. Specifically, we consider the cases in which firms share initial knowledge only (reciprocal cross-licensing), new knowledge only (Technology Sharing Cartel), and one involving full reciprocal knowledge transfer (similar to a patent pool). These cases are compared to each other, and to the initial benchmark situation in which firms go it alone. We find that some kind of cooperative agreement will always dominate the go-it-alone solution; we use the analysis to delineate situations in which cooperation should involve transfer of all or just new knowledge, and show that simply sharing prior knowledge is dominated by the other cooperative agreements. We consider the effects of knowledge sharing on R&D, and draw conlusions for industrial policy and firm strategy.

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1 Introduction

The existing stock of knowledge in an industry - measured in terms of patents for instance - may be asymmetrically spread between firms. Building upon existing knowledge through fresh Research and Development (R&D) is important both for process and product innovation, and generally for economic growth. In this paper, we consider the effects that the initial distribution of knowledge has on firms' incentives to undertake new R&D activity, and we look at the consequences of various types of knowledge sharing strategies. An influential branch of the R&D literature, starting with the seminal paper by d'Aspremont and Jacquemin (1988), looks at knowledge transfer as an unintended by-product of the R&D process, a spillover between firms. Later work by among others Katsoulacos & Ulph (1998), Kultti & Takalo (1998) and Poyago-Theotoky (1999) has endogenized the size of the spillover so that knowledge transfer - to the extent that this is optimal - becomes a conscious decision of the firms. An alternative formulation of the spillover makes it dependent upon the type of cooperative agreement that the firms enter into (Kamien, Muller & Zang, 1992). Common to all of these models is an underlying production game in which R&D has a deterministic effect on the marginal cost of production; the marginal cost in itself is implicitly assumed to embody all previous technological progress. Since firms are usually taken to be symmetric at the outset, one can interpret this as an even spread of existing knowledge.

However, acquiring knowledge has become a conscious part of firms' strategy, and markets for this knowledge have arisen in many industries (see Arora et al, 2001). Indeed, Cohen et al (2002) have identified several reasons that firms acquire and patent knowledge, and one of these is to use as a bargaining chip in cross licensing agreements or other forms of technology access. This is echoed by Rivette and Klein (2000; 6) who state that "Owning intellectual property lets companies develop very favourable partnerships and licensing relationships". Hence, one cannot take as given an even distribution of prior knowledge. In cumulative innovation, one can consider that existing knowledge must be built upon to achieve an overall goal. Some firms may be closer to the goal than others at any point in time. We consider firms that may have initially different stocks of knowledge, but that must add to this to increase the chances of making an innovation. In biotechnology for example, there are different general platform tools that are developed upstream for the testing of the action of molecules, drug design and the production of gene-chips downstream (Arora et al, 2001; 160-161). Access to this technology is a prerequisite for being able to compete in the downstream R&D market. While some firms have specialized themselves as providers of these platform tools, there is evidence that some firms are active both upstream and downstream.[1] Given the initial stock of knowledge and its distribution, what factors might affect the decisions of firms to exchange this knowledge, and how does this affect the extent of ongoing R&D? These are fundamental questions that we address in this paper.

Suppose that an innovation is cumulative so that it combines already existing knowledge with new R&D. Several firm strategies for the exchange of information can be identified here, depending upon whether they exchange existing knowledge only, future results of R&D only, or a combination of both.[2] All of these information sharing strategies can be compared to a go-it-alone benchmark in which there is no cooperation. When only prior knowledge is exchanged, one can aliken this to a reciprocal cross-licensing of existing patents, and when only new information is shared this would correspond to a forward-looking Technology Sharing Cartel (TSC).[3] The case in which existing and future knowledge are shared among firms can be alikened to a patent pool.[4] In our model, innovation is uncertain but is increasing in the level of knowledge of each firm. Discoveries are not necessarily exclusive, and firms can innovate a viable product that makes them compete in the post R&D market.[5] In the analysis, we show that some form of cooperative agreement can always increase industry profit compared to the go-it-alone solution. Reciprocal cross-licensing of existing information is always dominated by an TSC or patent pool. Which of the TSC and patent pool maximizes industry returns is shown in the analysis to depend upon the degree of competition in the post R&D market and the degree of asymmetry in the distribution of the initial stock of knowledge.

[1] See Joly & de Looze (1996) for the case of plant biotechnology.

[2] In the analysis, we focus on reciprocal exchange of different types of information and the effects that this has on R&D. We abstract from any royalty payments or licensing fees.

[3] See Petit and Tolwinsky (1999).

[4] There are many types of patent pools and some of these involve licensing all patents to a third party that then arranges production. Here we assume that the research firms can benefit from the innovation directly.

[5] One could imagine different biomedicines that are similar in design and effect for example, but distinct enough to be considered different products.

Our model of knowledge creation and transfer has also an alternative interpretation. The existing stock of knowledge may be thought of as basic research that has been at least partly funded by public authorities, and R&D carried out by firms is then applied research aimed at developing commercializable products. The distribution of the initial stock of knowledge can then be interpreted as reflecting public policy towards the financing of basic research. At the two extremes, one can imagine a policy of "picking winners" in which all funding is directed towards a single firm, and a neutral policy in which the funds for basic research are spread evenly between firms. Our analysis then looks at the implications of these policies for add-on R&D and the knowledge-sharing strategies of firms.

The effect of existing knowledge on future R&D and cooperative strategies is of particular relevance for nascent industries such as those built on nanotechnology. Bawa (2005) discusses the "patent land-grab" that is occurring in nanomedicine in which firms are aggressively filing broad patent claims relating to the five basic nanomaterials in the hope of creating toll booths for future development and commercialization of products based on these. Our analysis highlights conditions under which firms in an industry can benefit from untangling and sharing their intellectual property.

The paper is organized in 9 Sections. Following this introduction, the general model is outlined in Section 2. Four different cases, non-cooperation and three cooperative arrangements, are presented in Section 3, 4, 5 and 6. The incentives for cooperation are discussed in Section 7 and 8, and Section 9 concludes.

2 The general model

There are two risk-neutral firms, indexed by $i = 1, 2$, who compete to make an innovation. In order to be successful, the level of knowledge that a firm must possess must be above some threshold level which is determined stochastically by independent draws from a uniform probability function defined on the interval [0,1]. Each firm begins the game with an amount of knowledge $1 > \mu_i \geq 0$, and can add to this through two channels: knowledge trading or knowledge production. The latter involves independent investments in R&D where the amount of extra knowledge created by firm i is given by x_i at a cost of $\frac{x_i^2}{2}$. We open up for the possibility that the production of new knowledge may spill over from one firm to another.[6] Given the firms' initial level of knowledge (however acquired), each has the option of investing in R&D to add to this level; then they get an independent draw from the probability distribution to determine whether they have been successful in making the innovation. Success or failure is then publicly revealed, and the firms compete in the product market at stage 2. Firm i earns a profit of $(1-a)$ if both firm i and j succeed, 1 if i succeeds and j fails (monopoly profit is normalized to unity), and zero if i fails. The profits to firm j are defined symmetrically. The parameter a is contained in the interval $[1/2, 1)$ depending on product market competition with one half corresponding to collusion and as we approach unity the limit case of Bertrand competition with identical products would emerge.[7]

Suppose that the stock of knowledge that firm i possesses initially is given by μ_i, whilst the amount of new knowledge created by this firm is identical to its R&D level x_i. Without loss of generality we shall assume that $\mu_i \geq \mu_j$. We allow for the possibility that the rival firm's knowledge and knowledge creation can affect the own probability of innovation by supposing that i gets a share of j's knowledge: $\alpha x_j + \delta\mu_j$. Here α and δ take the values 0 or 1 to indicate which, if any, type of knowledge is transferred. We shall use these parameters to delineate different cases in the analysis. Given the structure of the model, the probability that firm i $(i = 1, 2)$ succeeds in innovating with R&D expenditure x_i is given by the cumulative density function, $F_i\left(x_i, x_j; \mu_i, \mu_j\right) \equiv x_i + \mu_i + \alpha x_j + \delta\mu_j$.

The expected net profits to firm i $(i, j = 1, 2, i \neq j)$ at stage 2 is given by

$$E\Pi_i = F_iF_j(1-a) + F_i\left(1-F_j\right) - \frac{x_i^2}{2}. \tag{1}$$

Making the necessary substitutions, and rearranging gives

$$E\Pi_i = \left(x_i + \mu_i + \alpha x_j + \delta\mu_j\right)\left(1 - a\left(x_j + \mu_j + \alpha x_i + \delta\mu_i\right)\right) - \frac{x_i^2}{2} \tag{2}$$

[6] This is in line with the vast majority of the R&D literature in this field such as d'Aspremont and Jacquemin (1988) and Kamien, Muller and Zang (1992). The first posits spillovers between R&D outputs (unit cost reductions) and the latter between R&D inputs (R&D expenditures).

[7] The limit case of $a = 1$ is not consistent with an interior equilibrium, however. This becomes apparent later in this section.

The first order condition for a maximum, and corresponding reaction function is given by

$$\frac{\partial}{\partial x_i} E\Pi_i = 0 \Longleftrightarrow x_i = \frac{1 - a x_j(1+\alpha) - a\mu_j(1+\alpha\delta) - a\mu_i(\alpha+\delta)}{1+2a\alpha} \tag{3}$$

Here we are assuming an interior solution: obviously a firm will not continue with R&D beyond the point where $x_i + \mu_i + \alpha x_j + \delta \mu_j = 1$ since this activity would then entail a cost and no corresponding benefit.[8]

R&D expenditures are strategic substitutes in this model since $dx_i(x_j)/dx_j < 0$ from (3).

Solving the reaction functions of the firms simultaneously gives equilibrium R&D expenditures in the general case as

$$x_i^* = \frac{1}{\Theta}\left[\Phi\mu_i + \Omega\mu_j + \Gamma\right] \tag{4}$$

where the denominator $\Theta > 0$ by the stability condition (see Seade, 1980, for a general analysis, and Henriques, 1990 for the application of the stability condition to R&D games). The expressions for $\Phi, \Theta, \Omega, \Gamma$ are

$$\begin{aligned}
\Theta &\equiv (1 + 3a\alpha + a)\,(1 - a(1-\alpha)) \\
\Phi &\equiv -a(-a + \alpha + \delta + a\alpha) \\
\Omega &\equiv -a\,(1 - a\delta + \alpha\delta + a\alpha\delta) \\
\Gamma &\equiv 1 - a(1-\alpha)
\end{aligned}$$

The stability condition implies that $a(1-\alpha) < 1$, so Γ is positive and Ω is negative. Hence, equilibrium R&D level falls with the rival's level of prior knowledge. When no knowledge is exchanged, Φ is positive, else negative. Hence, equilibrium R&D level falls (increases) with own level of prior knowledge when (no) knowledge is exchanged When $\alpha = 1$ or $\delta = 1$ then $\Phi = \Omega$ and the solution of the R&D problem will be symmetric. This implies that we will get a symmetric solution for the R&D level if prior knowledge only is exchanged ($\delta = 1$), or if both types of knowledge are exchanged ($\alpha = \delta = 1$). The actual R&D levels will vary between these cases, however, and we return to this below. First, we analyze a benchmark case in which no knowledge transfer occurs (i.e. a fully non-cooperative solution).

[8] Existence conditions for the equilibria are taken up below.

3 Benchmark non-cooperative case

When the firms do not exchange knowledge of any sort we have that $\alpha = \delta = 0$. Inserting in (4), we obtain the go alone or benchmark solution

$$x_i^B = \frac{(1-a) + a\left(\mu_i a - \mu_j\right)}{(1-a)(1+a)} \tag{5}$$

where the "B" superscript refers to the benchmark case. To facilitate comparison with the other cases that we consider in the paper, it is convenient to write $\mu_i \equiv b\mu$ and $\mu_j \equiv (1-b)\mu$ with $\mu \equiv \mu_i + \mu_j$ and $b \in [1/2, 1]$ where $b = 1/2$ means $\mu_i = \mu_j$, and $b = 1$ means $\mu_i = \mu$ and $\mu_j = 0$. Since $b \geq \frac{1}{2}$ we are assuming that i is always at least as knowledgeable at the outset as j (and this is without loss of generality). Hence the parameter μ captures the aggregate level of pre-R&D knowledge, and b its distribution between firms. Inserting into (5) gives

$$x_i^B = \frac{(1-a) + a\left(ba - (1-b)\right)\mu}{(1-a)(1+a)} \tag{6}$$

$$x_j^B = \frac{(1-a) + a((1-b)a - b))\mu}{(1-a)(1+a)} \tag{7}$$

The interior solution in (5) is valid as long as $x_i^B \geq 0$, the stability condition is fulfilled, and the requirement that the probability of innovation is at most 1. This latter condition, limiting the amount of asymmetry between the firms, can be written as:

$$b \leq \frac{(1-a)a + a\mu}{(1+a)\mu} \equiv \bar{b}$$

Indeed $b \leq \bar{b}$ also guarantees that R&D levels are positive, and it is straightforward to verify that the most knowledgeable firm at the outset will have the largest R&D and the largest chance of innovating. Observe that the feasible asymmetry that is consistent with an interior equilibrium depends on the level of competition and the level of aggregate prior knowledge. For maximum competition (a approaching 1) any substantial degree of asymmetry is precluded since $\bar{b}$ approaches 1/2. If competition is softer any asymmetry is permissible provided aggregate prior knowledge is small enough.

Note that the sum of R&D in the benchmark case is independent of the distribution of μ since

$$X^B \equiv x_i^B + x_j^B = \frac{2 - a\mu}{1 + a}$$

For this to be an equilibrium requires also that the expected profit be non-negative. This can be written implicitly as:

$$E\Pi_i^B = \frac{x_i^B(x_i^B + 2b\mu)}{2} \quad (8)$$

$$E\Pi_j^B = \frac{x_j^B(x_j^B + 2(1-b)\mu)}{2} \quad (9)$$

so that $E\Pi_i^B, E\Pi_j^B \geq 0$ as long as the R&D levels are non-negative. It is easily verified that $E\Pi_i^B \geq E\Pi_j^B$ for $b \geq \frac{1}{2}$with equality for like prior knowledge ($b = \frac{1}{2}$).

The relative properties of this benchmark case are summed up in Proposition 1, where we have written the probability of innovation for each firm simply as F_i^B and F_j^B.

Proposition 1 *$x_i^B \geq x_j^B$, $F_i^B \geq F_j^B$, and $E\Pi_i^B \geq E\Pi_j^B$ for $b \in \left[\frac{1}{2}, 1\right]$.*

Some comparative static properties of the interior equilibrium are straightforward to verify. The more biased the initial distribution of knowledge is towards i, the more R&D will this firm have and the less will the competitor have: $\frac{\partial x_i^B}{\partial b} > 0$, $\frac{\partial x_j^B}{\partial b} < 0$; this effects cancel out in aggregate since $\frac{\partial X^B}{\partial b} = 0$. In aggregate, an increase in μ will lead to a fall in R&D: $\frac{\partial X^B}{\partial \mu} < 0$. The effect that an increase in the aggregate level of knowledge will have on R&D at the firm level depends upon b:

$$\frac{\partial x_i^B}{\partial \mu} > 0, \frac{\partial x_j^B}{\partial \mu} < 0 \text{ for } b \in (\tfrac{1}{1+a}, 1] \quad (10)$$

$$\frac{\partial x_i^B}{\partial \mu} < 0, \frac{\partial x_j^B}{\partial \mu} < 0 \text{ for } b \in [\tfrac{1}{2}, \tfrac{1}{1+a}) \quad (11)$$

When there is little difference between the firms initially (small b) then initial knowledge substitutes for new R&D for both firms; for a sufficiently large difference, the leader will increase its R&D in response to an increase in the initial level of aggregate knowledge. Comparative static results relating to the effect of a on R&D at the firm level are less transparent. However, we have that $\frac{\partial X^B}{\partial a} < 0$.

Differentiating (6) implicitly with respect to b reveals that $\frac{\partial E\Pi_i^B}{\partial b} > 0$, $\frac{\partial E\Pi_j^B}{\partial b} < 0$. The less evenly distributed initial knowledge is, the better (worse) is this for the expected payoff of the leader (laggard). Whenever an increase in μ increases a firm's R&D this will have the same effect on expected profit. Hence $\frac{\partial E\Pi_i^B}{\partial \mu} > 0$ for sufficiently large b (cf (10)). Additionally, $\frac{\partial E\Pi_i^B}{\partial \mu} > 0$ for all values of b as long as the initial level of knowledge is sufficiently large ($\mu > \frac{2}{a(a+2)}$). Since $\frac{\partial^2 E\Pi_i^B}{\partial \mu} > 0$, lower levels of μ can lead to $\frac{\partial E\Pi_i^B}{\partial \mu} < 0$ for low enough b. The effect that μ has on $E\Pi_i^B$ works through several channels; an increase in this parameter increases the probability that i will successfully innovate for any given knowledge distribution and R&D expenditure; in some cases (i.e. for large enough b) this will also increase x_i^B directly, increasing R&D cost. This latter effect is partly mitigated by the fact that an increase in μ will reduce x_j^B directly and i's strategic response to this is to reduce R&D, saving cost. The total effect is positive. When b is small, however, and increase in μ will lead to less own R&D by i saving cost, and reducing the probability of successful innovation. For j one finds that when the firms are fairly equal at the outset then $\frac{\partial E\Pi_j^B}{\partial \mu} > 0$, whilst this result is reversed for larger levels of inequality.

Although less elegant than (8) and (9), it is convenient for later comparisons to express average expected profit, $E\Pi^B$, as a quadratic function of μ,

$$\begin{aligned} E\Pi^B &\equiv (E\Pi_i^B + E\Pi_j^B)/2 = A_B\mu^2 + B_B\mu + B_B \qquad (12) \\ &\quad \text{where} \\ A_B &\equiv \frac{4a(b-1)b + a(1-2b(1-b))(3a-a^3)}{4(a^2-1)^2} \\ B_B &\equiv \frac{1}{2\left(1+a\right)^2} > 0 \end{aligned}$$

We cannot in general sign A_B so expected benchmark payoff may be a concave or convex function of μ depending on b and a, but observe that

A_B is increasing in b (hence at a minimum for $b = 1/2$), negative under perfect symmetry ($b = 1/2$) and positive under complete asymmetry ($b = 1$) regardless of degree of product market competition. We will return to this expression in Section 8.

4 Transfer of prior knowledge - cross licensing

We assume that the required parameter restrictions for equilibrium are fulfilled and start out by looking at partial cooperation in the sense of transfer of prior knowledge only. Writing $\mu \equiv \mu_i + \mu_j$, and inserting $\alpha = 0, \delta = 1$ into (4) gives the equilibrium R&D level

$$x^P = \frac{1 - a\mu}{1 + a}$$

Note that the R&D level is independent of the distribution of prior knowledge, and that prior knowledge is a substitute for new R&D. We see that $x^P > 0$ if $1/a > \mu$ which is always true since $1/a \geq 1 > \mu$ so that knowledge exchange can never preclude the production of new knowledge. In addition, we require that the interior solution generates a probability of innovation that does not exceed 1:

$$\mu \leq a$$

For the equilibrium to be defined requires that each firm should earn a non-negative profit in equilibrium. The expected profit of each firm can be determined as:

$$E\Pi^P \equiv A_P\mu^2 + 2B_B\mu + B_B \tag{13}$$

where

$$A_P \equiv \frac{-a\,(2 + a)}{2\,(1 + a)^2} < 0$$

Hence, the expected profit is a concave function of μ. One can easily verify that (13) has one positive an one negative root and that the positive root is equal to $1/a$, ensuring positive profit. Also observe that expected profit is a maximum for $\mu = 2/(a(2 + a))$. The next proposition states necessary conditions for existence of this equilibrium; here we have written F^P for the common probability of success in equilibrium

Proposition 2 *$E\Pi^P \geq 0$ and $x^P > 0$ and $F^P \leq 1$ for $\mu \leq a$.*

The next proposition compares the amount of R&D that arises in equilibrium in the two scenarios that we have considered up to now.

Proposition 3 *(i) If $\bar{b} \geq b > \frac{1}{1+a}$ then $x_i^B > x^P > x_j^B$ and $x_i^B + x_j^B > 2x^P$; (ii) if $\frac{1}{1+a} > b \geq \frac{1}{2}$ then $x^P < x_i^B$ and $x^P < x_j^B$.*

In case (i) firm i is sufficiently advantaged compared to j.[9] Here, the more (less) knowledgeable firm will undertake less (more) R&D after exchanging information compared to the benchmark case. When firms are more similar as in (ii) knowledge exchange acts as a substitute for new R&D. One sees immediately that the aggregate amount of R&D decreases after knowledge exchange in case (ii). For case (i), it is easily verified that aggregate R&D falls after knowledge exchange, so that the increase by the inferior firm at the outset does not counter the fall in R&D activity of the initial leader. Recall that a is the premium to being the only firm in the product market; as this parameter increases, we are most likely to be in case (i) for a given b.

Proposition 4 indicates the effect that the exchange of prior knowledge has on the probability of innovation.

Proposition 4 *(i) If $\bar{b} \geq b > \frac{1}{1+a}$ then $F_i^B > F^P > F_j^B$ (ii) If $\frac{1}{1+a} > b \geq \frac{1}{2}$ then $F^P > F_i^B \geq F_j^B$.*

In case (i) the most advanced firm increases its probability of innovation whilst the least advanced firm has a lower chance of innovation than in the benchmark case. Although this firm absorbs the knowledge of the rival, it is outweighed by its reduction in R&D in terms of the effect on the probability of innovation. Propositions 3(ii) and 4(ii) indicate that even though similar firms will reduce their own R&D effort after knowledge exchange, the net effect on the innovation probability is positive.

[9] The existence condition in Proposition 2 guarantees that there are feasible b that fall in this range, i.e. that $\bar{b} \geq \frac{1}{1+a}$.

5 Transfer of new knowledge - Technology Sharing Cartel

Consider the case in which firms do not share their prior knowledge, but agree to allow reciprocal access to new knowledge ($\alpha = 1$, $\delta = 0$). The amount of R&D undertaken by each firm is

$$x^N = \frac{1 - a\mu}{(1 + 4a)} \tag{14}$$

where $\mu < \frac{1}{a}$ secures positive investment. The constraint on the innovation probability gives a further restriction that the most advanced firm at the outset must have $F_i = b\mu + 2x^N < 1$. Hence positive investment and less than certain innovation require that $\mu < \min\{\frac{4a-1}{b(1+4a)-2a}, \frac{1}{a}\}$. The innovation probability constraint is binding when $b < a$. Given that the initial level of knowledge is not equalized in this case, the expected payoffs of the firms will be asymmetric. For the interior equilibrium to exist further requires that the least advantaged firm has a non-negative profit. Analytically, this is a difficult condition to tie down concisely. However, the previous existence conditions are also echoed here since the expected profit of j is always positive for sufficiently low μ.

The average expected payoff in this case can be worked out as

$$\begin{aligned} E\Pi^N &= A_N\mu^2 + B_N\mu + C_N \qquad (15)\\ &\text{where} \\ A_N &= \frac{a\left(3a - 2b + 16ab^2 - 32a^2b + 32a^2b^2 - 16ab + 8a^2 + 2b^2\right)}{2\left(4a+1\right)^2} \\ B_N &= \frac{1}{2}\frac{2a+1}{\left(4a+1\right)^2} > 0 \\ C_N &= \frac{8a+3}{2\left(4a+1\right)^2} > 0 \end{aligned}$$

The sign of A_N is negative for low values of a and b, becoming positive as they increase. More precisely, we have that $A_N \gtrless 0$ for $b \gtrless \widetilde{b}$ where $\widetilde{b} = \frac{1}{2} + \frac{\sqrt{2a+1}}{2(4a+1)}$. When $b > \widetilde{b}$ then $E\Pi^N$ is convex and strictly increasing in

μ, and is positive at $\mu = 0$. When $b < \widetilde{b}$ then $E\Pi^N$ is concave in μ, positive valued and increasing at $\mu = 0$. To check that $E\Pi^N > 0$ for all permissible parameter values, we can check what happens at $\mu = \frac{1}{a}$ for $b > a$ and at $\mu = \frac{4a-1}{b(1+4a)-2a}$ for $b < a$. If the expected profit is positive here then it will be positive for all smaller values of μ. We find indeed that $E\Pi^N(\mu = \frac{1}{a}) > 0$ and that $E\Pi^N(\mu = \frac{4a-1}{b(1+4a)-2a}) > 0$ for $b > a$, so that the average expected profit is positive for all permissible parameter values.

6 Full transfer of knowledge - Patent pools

We now consider full transfer of both existing and new knowledge. In this case the parameters are $\alpha = \delta = 1$:

$$x^F = \frac{1 - 2a\mu}{1 + 4a}$$

Again the level of R&D is only dependent upon aggregate prior knowledge and not its distribution. We observe that $x^F > 0$ if $1/(2a) > \mu$ so an agreement on transfer of all knowledge may prevent any production of new knowledge if the initial knowledge levels of the firms are too large or when product market competition will be hard. The interior solution must generate a probability of innovation that does not exceed 1:

$$\mu \leq 4a - 1$$

This condition is fulfilled whenever there is production of new knowledge since $4a - 1 \geq 1/(2a)$. The expected payoff must be non-negative in equilibrium and is determined as

$$\begin{aligned} E\Pi^F &= A_F\mu^2 + 2B_N\mu + C_N \qquad (16) \\ &\text{where} \\ A_F &\equiv -\frac{a(1+2a)}{(4a+1)^2} < 0 \end{aligned}$$

Hence the expected profit in this equilibrium is concave in the gross prior level of knowledge and again there will be a positive and a negative root.

For positive levels of R&D the restriction imposed by non-negative payoff will not be binding. This can be seen by observing that the positive root in this case must exceed the positive root when only prior information was exchanged (equal to $1/a$, exceeding the requirement for positive R&D, equal to $1/(2a)$). These results are summed up in the next proposition:

Proposition 5 $E\Pi^F \geq 0$ *and* $x^F > 0$ *and* $F^F = \mu + 2x^F \leq 1$ *for* $\mu \leq \frac{1}{2a}$.

7 Comparing knowledge transfer

In order to evaluate the incentives for cooperation, at the very least we need to look at aggregate expected profits. If the expected average benchmark payoff exceeds the cooperative expected payoff, then a cooperative agreement between the two firms will not be enforceable. In the opposite case, the industry as a whole will expect to gain from cooperation so that some kind of agreement to cooperate might be feasible. This agreement might entail sidepayments if one firm loses and one gains relative to the benchmark. The same comparison must be done among the different cooperative cases. The relevant information for the different cases are summarized below.

Case	Average expected profit	Restrictions on prior knowledge
Benchmark	$E\Pi^B \equiv A_B\mu^2 + B_B\mu + B_B$	$\mu \leq a(1-a)/(b(1+a)-a)$
Prior	$E\Pi^P \equiv A_P\mu^2 + 2B_B\mu + B_B$	$\mu \leq a$
New	$E\Pi^N \equiv A_N\mu^2 + B_N\mu + C_N$	$\mu \leq (4a-1)/(b(1+4a)-2a)$
		and $\mu \leq 1/a$
Full	$E\Pi^F \equiv A_F\mu^2 + 2B_N\mu + C_N$	$\mu \leq 1/(2a)$

Let us start by observing that expected profits in the case of transfer of prior knowledge only given by equation (13), degenerates to benchmark profits given by the trem C_B when there is no prior knowledge. Expected profits in case of full cooperation or exchange of new knowledge is then equal to the term C_N, and exchange of knowledge is therefore preferred to not sharing since $C_N > C_B$. In other words, allowing spillovers constitutes a self-enforcing equilibrium when there is no prior knowledge. This is consistent with a decision to apply identical R&D approaches to facilitate spillovers as suggested by Wiethaus (2005), but not consistent with a decision to apply idiosyncratic R&D approaches to prevent spillovers as suggested by Kamien and Zang (2000). When there is prior knowledge that may be exchanged, the picture is more complicated and we will shortly see that the results may be consistent with firms limiting spillovers as well, although they will not wish to prevent spillovers altogether.

We will first compare the cooperative arrangements. Symmetry is the striking feature of the cooperative equilibria. When the firms' knowledge is totally compatible, or equivalently the spillover is perfect, the firms have an identical R&D effort even though they are different at the outset. This phenomenon is independent of the type of knowledge - new or "old" - that is exchanged. Consequently, the technological leader at the outset will also have the greater chance of making the innovation after the R&D stage. In this sense, one can say that participation in knowledge exchange will preserve the initial competitive edge of the leader.

Comparing full cooperation to exchange of prior information, the difference in expected payoff is

$$\Delta FP \equiv E\Pi^F - E\Pi^P = (A_F - A_P)\mu^2 + 2(B_N - B_B)\mu + C_N - B_B$$

The difference is a convex function in μ (i.e. $A_F - A_P > 0$) , positive for μ equal to zero since $C_N - B_B > 0$ and with a negative slope in the same point since $B_N - B_B < 0$. It can easily be verified that $(A_F - A_P)(C_N - B_B) > (B_N - B_B)^2$ so there are no real roots. Hence, we have

Proposition 6 $E\Pi^F > E\Pi^P$

Full cooperation is always preferred to sharing of prior information only.

For comparing the case of exchange of new knowledge to that of prior knowledge only, define

$$\Delta NP \equiv E\Pi^N - E\Pi^P = (A_N - A_P)\mu^2 + (B_N - 2B_B)\mu + C_N - B_B$$

where the signs can be determined as follows for the relevant range of a and b: $A_N - A_P > 0$, $B_N - 2B_B < 0$, $C_N - B_B > 0$. Hence ΔNP is a convex function of μ. However, there are no real roots of this function either and hence $\Delta NP > 0$. Thus

Proposition 7 $E\Pi^N > E\Pi^P$

Propositions 6 and 7 demonstrate that of the cooperative arrangements, P is the worse.

Comparison of the other cases does not lend itself so easily to analytical examination. We have therefore undertaken a numerical analysis of the knowledge transfer strategies that we consider. In this analysis, one must bear in mind that the strictest existence conditions for the cases under consideration must always be fulfilled. When the difference between the industry profits under two compared regimes has a positive root, we check whether this root is permissible to see whether there is a sign change in this difference.

Let us now compare $E\Pi^N$ to $E\Pi^F$ by defining

$$\Delta FN \equiv E\Pi^F - E\Pi^N = (A_F - A_N)\mu^2 + B_N\mu$$

where $A_F - A_N < 0$ and $B_N > 0$ so ΔFN is a concave function of μ with $\Delta FN = 0$ for $\mu = 0$ and $\mu \equiv \mu^+_{FN} = B_N/(A_F - A_N)$ if this positive root is within the feasible area for existence. Since ΔFN is a concave function of μ with one positive root, we can compute ΔFN for the largest permissible level of μ. If this value is positive then we know that $\Delta FN > 0$ for all permissible μ up to this level; if, on the other hand, we observe that $\Delta FN < 0$ for the maximum μ, then there must exist a critical level of aggregate prior knowledge, below which exchange of new knowledge will be feasible and above which it will not. If ΔFN is negative for any feasible pair (a, b), we know that the firms could do better by exchanging new knowledge rather than all knowledge for this (a, b) combination.

a \ b	.5	.6	.7	.8	.9	1.0
.5	+	+	+	+	+	+
.6	+	+	+	-	-	-
.7	+	+	+	-	-	-
.8	+	+	-	-	-	-
.9	+	+	-	-	-	-
1.0	+	+	-	-	-	-

Table 1. Sign of ΔFN

It turns out that average expected payoff from sharing all knowledge tends to be higher than from sharing new knowledge if initial knowledge is evenly distributed or if competition in the product market is soft. If competition is tough or the initial stock of knowledge is rather different, the firms are on average better off by only sharing new knowledge. This is illustrated in Table 1 where the sign of ΔFN for different values of (a, b) is presented. It is interesting that limited sharing, presumably easier to implement, is dominant for a wide set of values. We observe that competition and asymmetry are substitutes in determining what case gives the highest expected payoff. The results from comparing full cooperation to exchange of new knowledge are summed up in the proposition below.

Proposition 8 $E\Pi^F < E\Pi^N$ *for* $\mu_{FN}^+ < \mu \leq \min[(4a-1)/(b(1+4a)-2a), 1/(2a)]$ *where* $\mu_{FN}^+ \equiv \mu : \{\Delta FN = 0$ *and* $\mu > 0\}$ *and* $E\Pi^F \geq E\Pi^N$ *for* $0 < \mu \leq \min[\mu_{FN}^+, (4a-1)/(b(1+4a)-2a), 1/(2a)]$

Proposition 8 along with proposition 6 and 7, gives a complete ranking of the cooperative cases in terms of average expected payoff.

8 Comparing knowledge transfer to benchmark

Having ranked knowledge transfer strategies at the industry level, we proceed to compare these to the benchmark non-cooperative case. Since case P is dominated by the other cooperative strategies, we leave this out of the comparison. Let us first look at full cooperation compared to expected benchmark payoff on average for the two firms. Writing the difference in aggregate average expected profits,

$$\Delta FB \equiv E\Pi^F - E\Pi^B = (A_F - A_B)\mu^2 + (2B_N - B_B)\mu + C_N - B_B$$

it can easily be shown that $2B_N - B_B \leq 0$ with strict inequality for $a > 1/2$, and that $A_F - A_B < 0$. Hence the difference is decreasing and concave in μ so $\Delta FB < 0$ for sufficiently large μ if such values are consistent with existence of equilibrium.

Again, we compute ΔFB for the maximum μ permitted and see whether it is negative or not for different combinations of a and b. If negative, it means that benchmark gives higher average expected payoff than sharing all knowledge for the specific (a, b) and there must be a smaller critical value for μ where this no longer is true. Results for a subset of (a, b) are presented in Table 2, where + means ΔFB is positive; values of a less than those indicated in the table yield $\Delta FB > 0$ for all values of b.

		b					
		.5	.6	.7	.8	.9	1.0
	.90	+	+	+	+	+	+
	.91	+	+	+	+	+	-
	.92	+	+	+	+	-	-
	.93	+	+	+	-	-	-
a	.94	+	+	-	-	-	-
	.95	+	+	-	-	-	-
	.96	+	-	-	-	-	-
	.97	+	-	-	-	-	-
	.98	+	-	-	-	-	-
	.99	+	-	-	-	-	-

Table 2. Sign of ΔFB

ΔFB is positive in most cases, but negative for certain pairs (a, b) provided a is large. Hence, firms will never go alone if competition in the product market is soft. Furthermore, the degree of asymmetry and degree of competition are substitutes in determining whether the benchmark non-cooperative case is preferred or not.

The results from comparing full cooperation to the benchmark are summed up in the proposition below. The condition for preferring benchmark to cooperation means a has to be large if benchmark is to dominate (by implication μ has to be small in order to keep the innovation probability well defined, but this is an artefact of the model). Intuitively, this is reasonable since the benefit from succeeding alone will be greater when a is large.

Proposition 9 $E\Pi^F < E\Pi^B$ *for* $\mu_{FB}^+ < \mu \leq a(1-a)/(b(1+a)-a)$ *where* $\mu_{FB}^+ \equiv \mu : \{\Delta FB = 0$ *and* $\mu > 0\}$ *and* $E\Pi^F \geq E\Pi^B$*for* $0 < \mu \leq \min[\mu_{FB}^+, a(1-a)/(b(1+a)-a), 1/(2a)]$

It now only remains to compare exchange of new information to benchmark. Define

$$\Delta NB \equiv E\Pi^N - E\Pi^B = (A_N - A_B)\mu^2 + (B_N - B_B)\mu + C_N - B_B$$

where $B_N - B_B < 0$ and $A_N - A_B < 0$ for all relevant (a,b). Hence, ΔNB is a concave function of μ, positively valued with a negative slope for $\mu = 0$. Again, there will be one positive root, say μ_{NB}^+, so we know $E\Pi^N$ will exceed $E\Pi^B$ for sufficiently small μ. If the root does not violate the restrictions on μ under exchange of new knowledge and under benchmark, $E\Pi^B$ will exceed $E\Pi^N$ for large μ.

We proceed by employing the same approach as before by computing ΔNB for the maximum μ permitted and see whether it is negative or not for different combinations of a and b. If negative, it means that benchmark gives higher average expected payoff than sharing new knowledge for the specific (a,b) and there must be a smaller critical value for μ where this no longer is true. Results for a subset of (a,b) are presented in Table 3, where + means ΔNB is positive.

		b							
		.50	.51	.52	.53	.54	.55	.56	.57
	.5	+	+	+	+	+	+	+	+
a	.6	-	-	-	-	-	+	+	+
	.7	-	-	-	-	-	-	-	+
	.8	-	-	-	-	-	-	-	+
	.9	-	-	-	-	-	+	+	+

Table 3. Sign of ΔNB

We observe that sharing new knowledge gives higher average expected payoff than benchmark in most cases, and for all b larger than those in the table. The exception is for b close to 1/2 provided competition is not too soft and not too hard. A finer grid than in Table 3 reveals that for a closer to 1, benchmark payoff would only be larger for b almost equal to .5. The results are summed up as

Proposition 10 *$E\Pi^N < E\Pi^B$ for $\mu^+_{NB} < \mu \leq \min[a(1-a)/(b(1+a)-a), 1/a]$ where $\mu^+_{NB} \equiv \mu : \{\Delta FB = 0$ and $\mu > 0\}$ and $E\Pi^F \geq E\Pi^B$ for $0 < \mu \leq \min[\mu^+_{NB}, a(1-a)/(b(1+a)-a), 1/a]$*

Hence, we have that benchmark payoff may sometimes be larger than payoff from sharing new information and sometimes larger than from sharing all information. However, the results from the simulations also show that benchmark payoff is never higher than both simultaneously. Hence, going alone cannot be a self-enforcing equilibrium when sharing new knowledge and all knowledge both are allowed. This important result is summed up as

Proposition 11 *$E\Pi^B < \max[E\Pi^N, E\Pi^F]$*

9 Discussion

R&D policy goals are often made operational through specific targets for total and private R&D expenditures. In line with the Lisbon strategy many European countries have a target of 3 percent of GDP on total R&D spending, 2 percent private and 1 percent public. It is therefore interesting that we have an unambiguous ranking of the aggregate levels of private R&D in our model:

$$x_i^B + x_j^B > 2x^P > 2x^N > 2x^F$$

Hence, preventing or limiting cooperation would be beneficial to achieving ambitious targets on R&D spending. Although specific targets for R&D expenditures are commonly used in practical policy we should bear in mind that this is just attempts to make underlying objectives operational. Surely, aiming at a high level of R&D expenditures does not make sense if the probability of success and/or profits are higher with less effort. We have seen that maximum industry profit under the cooperative arrangements that give the least R&D always exceeds the level that can be obtained when the firms do not cooperate. If knowledge were tacit and therefore necessitated physical proximity to be exchanged, we expect that co-location, possibly in science parks or incubators, would be attractive. When knowledge is not tacit so that spillovers may take place irrespective of location, we would expect firms to choose identical R&D approaches rather than idiosyncratic ones as in Wiethaus (2005). If the policy instruments available are the aggregate level of prior knowledge through publicly funded basic research and the distribution of this between the firms (neutrality or picking winners), the Government may induce firms to choose exchange of new information (forming a TSC) rather than full cooperation (through a patent pool) and the other way around, but never to make firms go it alone. When there is some competition in the product market, an uneven distribution of initial knowledge is sufficient to make firms limit cooperation. Exchange of prior information through cross licensing is always dominated by the other cooperative arrangements.

The model predicts that tough product market competition and initial asymmetry in terms of knowledge tend to lead to less cooperation and more R&D, soft competition and initial equality to more cooperation and less R&D. These clear-cut predictions should in principle be verifiable empirically, either through use of field data or through experiments. We consider returning to the empirical issues in future research.

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