Mukherjee, Vivekananda; Ramani, Shyama V.

Working Paper

R&D cooperation, asymmetric technological capabilities and rationale for technology parks

Dresden discussion paper series in economics, No. 11/08

Provided in cooperation with:
Technische Universität Dresden

TU Dresden
Faculty of Business and Economics

Dresden Discussion Paper Series in Economics

R&D Cooperation, Asymmetric Technological Capabilities and Rationale for Technology Parks

VIVEKANANDA MUKHERJEE

SHYAMA V. RAMANI

Dresden Discussion Paper in Economics No. 11/08

ISSN 0945-4829

Address of the author(s):

Vivekananda Mukherjee
Jadavpur University
Department of Economics
700032 Calcutta
India

e-mail : mukherjeevivek@hotmail.com

Shyama V. Ramani
INRA-ALISS
65 Bd de Brandebourg
94205 Ivry sur Seine Cedex
France

e-mail : ramani@ivry.inra.fr

Editors:

Faculty of Business and Economics, Department of Economics

Internet:

An electronic version of the paper may be downloaded from the homepage:
http://rcswww.urz.tu-dresden.de/wpeconomics/index.htm

English papers are also available from the SSRN website:
http://www.ssrn.com

Working paper coordinator:

Dominik Maltritz
e-mail: wpeconomics@mailbox.tu-dresden.de

Dresden Discussion Paper in Economics No. 11/08

R&D Cooperation, Asymmetric Technological Capabilities and Rationale for Technology Parks

Vivekananda Mukherjee
Jadavpur University
Department of Economics
700032 Calcutta, INDIA
mukherjeevivek@hotmail.com

Shyama V. Ramani
INRA-ALISS
94205 Ivry sur Seine, FRANCE
ramani@ivry.inra.fr

Abstract:

Starting from the premise that firms are distinct in terms of their capacity to create radical product innovations, the present paper attempts to explore how firms choose between different forms of R&D cooperation and their consequences for social welfare. It studies a duopolistic market, where firms have to choose between R&D competition, a cost sharing alliance, an information sharing alliance or an R&D cartel. The paper demonstrates that asymmetry has an impact on alliance choice and social welfare. With similar firms, the cost sharing alliance will be preferred to R&D competition or any other form of collaboration. With significant asymmetry no alliance may be formed. In terms of social welfare, any alliance is preferable to R&D competition and the R&D cartel is the best. Given this inherent contradiction between private preferences and optimal social choice, the paper provides a rationale for public investment in terms of science and technology parks to promote R&D cartels.

JEL-Classification: L1, L24, L5

Keywords: R&D competition, R&D cooperation, technology parks

I. Introduction

While cooperation at the production and marketing stages between firms is nothing new, since the 1980's it is increasingly observed that firms competing in the same market, are initiating alliances at the research and development (R&D) stage. This phenomenon is particularly significant in the knowledge-based sectors like telecommunications, microelectronics, new materials and biotechnology. Growing costs, increasing technological uncertainty and increasing complexity of commercialization of innovations are said to be fueling the phenomenon of R&D cooperation. Governments of developed and developing countries have also started investing in science and technology parks, as a means for the State to support entrepreneurs and innovation creation. Such trends in the science-based sectors have stimulated an extensive theoretical inquiry on the incentives for inter-firm cooperation and the rationality of public investment. However, most of the literature examining the optimal mode of cooperation at the R&D level considers only symmetric firms. Clearly, the assumption of homogeneous firms is unrealistic, especially in emerging or fast evolving markets shaped by innovation (e.g. biotechnology, nanotechnology), where firm growth is conditioned by firm specific technological capability. Therefore, starting from the premise that firms are distinct in terms of their capacity to create innovations, the present paper attempts to explore how firms choose between different forms of R&D cooperation and their consequences for social welfare.

The two main questions examined in the economics literature on R&D collaboration are: when should firms initiate R&D collaboration instead of in-house investment? How can firms ensure that an R&D alliance will be successful given informational problems? While the first question is addressed by standard industrial organization models of competition and cooperation, the second question is more tackled by incomplete contract theory and transactions cost theory models (see Veugelers [1998]; and Sena [2004] for surveys). Naturally, a third complementary question, namely with which partner a firm should initiate R&D cooperation, becomes redundant when considering only symmetric firms.

In the strategic management literature, however, starting with the writings of Penrose [1959] who posited that the growth of firms is conditioned by their particular inherent resources and a desire to exploit these more fully, there has been a greater recognition of firm heterogeneity. A rich tradition of literature on strategic management has been built on this perspective to predict the strategies that firms would employ for growth and their impact on the core competencies of firms. In terms of R&D collaboration, this strand of literature has mainly examined the tradeoffs between buying technology from the market vs. creating innovation in-house or collaboration (see Caloghirou, Ioannides and Vonortas [2003] for survey).

Returning to the first central question examined in the industrial organization literature, the four most examined organizational modes for R&D investment are: (i) R&D competition, when firms decide on R&D investment independently; (ii) RJV or research joint venture, when firms share information but decide on R&D investment independently; (iii) R&D cost coordination or cost sharing, when firms coordinate or/and share the costs of R&D investment and (iv) R&D cartel, when firms coordinate to share costs and information so that the profit of the group is maximized. Stimulated by the seminal papers of Arrow [1962], Katz [1986], D'Aspremont and Jacquemin [1988] and Kamien, Muller and Zang [1992], there exists an extensive literature that has examined the impact of knowledge spillovers in a variety of contexts, such as with deterministic R&D, stochastic R&D, different degrees of market competition, different configurations of production costs, varying degrees of efficiency of R&D in the creation of product or process innovations (see Cabon-Dhersin and Ramani [2005] for survey). They yield two central results, which hold in markets with symmetric firms. First, when spillovers are high, R&D cooperation is more beneficial than R&D competition for both firms and society. Second, of the three modes of cooperation the R&D cartel yields the highest payoff for both firms and society.

With respect to consideration of asymmetric firms, there are a number of papers that show how heterogeneity can emerge given ex ante homogeneous firms in the context of R&D investment. Mill and Smith [1996] relate non-convexity in technology choices to uncertainty about demand or costs; while Amir and Wooders [1999] show that one-way spillovers can lead to different R&D investments among firms as a function of R&D costs and degree of spillovers and finally Van Long and Soubeyran [1999] demonstrate that if a mean preserving increase in the variance of the distribution of unit production costs can increase the profit of the group through differential R&D spreading, then asymmetry can also emerge. Other authors like Petit and Tolwinski [1999] and Kamien and Zang [2000] base their analysis on the assumption that a firm's potential for innovation depends not only on its current investment in R&D but also its accumulated R&D investment over time. In the former model, different R&D investment leads to different production costs, and while R&D cooperation leading to lower prices is beneficial for social welfare, R&D alliances may not be formed if firms are very heterogeneous and the impact on magnitude of R&D investment is difficult to predict. In the latter model, firms choose their "absorptive capacity" to learn from spillover-pools and also their ability to contribute to spillover-pools such that R&D collaboration generates sufficiently high spillovers and makes cooperation the attractive option.

A second stream has studied the presence of asymmetric strategies within R&D alliances formed of symmetric firms in terms of opportunism, where firms do not respect their commitments in terms of R&D effort or do not truthfully reveal some information pertinent to the alliance. Some models resolve the problems of moral hazard and adverse selection by the formulation of revelatory mechanisms and complete optimal contracts that render cooperation attractive (Gandal and Scotchmer [1993]; Morash [1995]. Others like Pérez-Castrillo and Sandonis [1997] and Bhattacharya, Glazer and Sappington [1992] attack the moral hazard problem through the formulation of appropriate reward and punishment mechanisms. Veugelers and Kesteloot [1996] consider firms engaged in cost reducing R&D, which could be asymmetric in terms of production costs, R&D investment and absorptive capacities but are symmetric in terms of opportunism. They find that asymmetries are important for successful joint ventures because when synergy yields are high, unequal bargaining shares compensate for incentives to cheat. Without attempting to eliminate opportunism, Chaudhuri [1999] also considers asymmetry in terms of cost of making the R&D effort and shows that increase in a mean preserving spread of costs can increase the probability of success as the more efficient firms invest more to make up for the free-riding by the less efficient firms. However, since this leads to lower R&D investment than outright mergers, he concludes that R&D collaboration is unlikely to occur if firms are very dissimilar.

Finally, a few papers start right from the beginning with asymmetric firms and explore the possibilities of R&D cooperation in the absence of adverse selection or moral hazard problems. Poyago-Theotoky [1997] studies an n-firm market with specialist and non-specialist firms, where the specialist firms can improve upon some of the characteristics of the good through R&D and she shows that depending on the extent of quality improvement R&D cooperation may or may not be socially desirable. Roller et al. [2007] extend the d'Aspremont and Jacquemin model of collaboration in cost reducing R&D to incorporate asymmetry in terms of different ex-ante marginal costs of production and they show that under both Cournot and Bertrand competition, significant asymmetry can lead to non-formation of alliances and cost-sharing is imperative to providing an incentive to collaborate. Clearly the present paper falls in this stream of literature with its consideration of heterogeneous technological capabilities ex-ante and the incentives generated consequently for R&D cooperation.

At the same time, our paper is distinct from others in this genre, due to three original features. It studies a duopoly market, where firms are endowed with specific innovation capabilities, given their historical trajectories, a feature not often examined in the literature. Second, the innovation considered is a radical product innovation, rather than a cost reducing process innovation, necessitating substantial R&D outlays. Third, since radical product innovations usually give rise to knowledge spillovers after commercialization rather than during the process of innovation creation, incentives for R&D alliances are examined in the absence of knowledge spillovers, thereby eliminating one of the most popular explanations for R&D cooperation.

The contribution of the paper to the existing industrial organization literature on R&D collaboration can then be understood in terms of its five central results.

First, the model shows that firms which are close in terms of their technological capability have a greater propensity to form an R&D alliance than asymmetric firms, thereby confirming an observation that has been repeatedly made in the empirical literature (Veugelers [1998]; Miotti and Sachwald [2003]; de Man and Duysters [2005]; Lopez [2008]) and in some of the theoretical papers discussed above.

Second, the paper confirms that in terms of R&D alliances, firms prefer to share costs only rather than share information only or share both costs and information. Again, it has been noted in several empirical analyses that cost sharing is crucial as incentive for the formation of R&D alliances (Miotti and Sachwald, 2003; de Man and Duysters, 2005).

Third, it proposes an explanation for the non-pervasiveness of R&D alliances. Theoretical models considering symmetric firms have shown that cooperation is beneficial to firms under many different situations, so that one is led to expect that cooperation at the R&D level will be a pervasive phenomenon. However this is not the case. Even in high tech sectors where R&D strategic alliances are more prevalent, cooperation at the R&D level is more the exception than the rule. We show that significant asymmetry in technological capabilities could be a cause of the problem.

Four, the model provides a rationale for public investment in science and technology parks for the hi-tech sectors. A social welfare ranking of the R&D alliances according to our model confirms the standard result that the R&D cartel is best for society. However, we also show that when firms are similar in terms of their technological capabilities, they will prefer to initiate a cost sharing alliance and if they are very asymmetric no R&D alliance may be formed at all. Therefore, in the face of such contradictions between social choice and private choice, public policy and investment promoting collaboration are called for.

Five, it also refines some standard theoretical results. For instance, an established result is that R&D competition yields highest payoffs to firms when spillovers are low.

However, we show that in the context studied with zero spillovers and a radical product innovation, although R&D competition always dominates an information sharing alliances, there are parameter configurations where a cost sharing alliance and an R&D cartel dominate R&D competition.

The rest of the paper is organized as follows. Section II presents the model. Section III contains the results: sections III(i)-III(iv) compare payoffs from R&D competition and the three R&D alliances; section III(v) explains firm preferences for R&D collaboration and section III(vi) examines implications for social welfare. Finally, section IV concludes.

II. The Model

Consider a firm in a hi-tech sector such as biotechnology or nanotechnology, which needs to invest first in the acquisition of a knowledge base in order to develop the technological capability to create a radical innovation, for which a potential market exists. For simplicity let us suppose that this investment is given by the fixed costs F, that could represent recruitment of new researchers, purchase of new machinery, installation of a new lab etc. This gives rise to a technological capability that enables the firm to create a radical innovation with probability p. Furthermore, let us suppose that a technology race occurs in a duopolistic market, with the two firms indexed by i and j. While the firms have the same cost of production ex-ante, they do not have the same history or managerial vision. Therefore, the acquisition of the same knowledge base can give rise to different firm specific dynamic technological capabilities[1] given by the probabilities p_i and p_j respectively. There are no spillovers or learning externalities in the market and hence the probabilities p_i and p_j are independent of one another. The ratio $\frac{p_i}{p_j} = \gamma$ (say) measures the degree of asymmetry in the technological competencies of the two firms. If $\gamma = 1$, the firms are symmetric and if $\gamma \neq 1$, the firms are asymmetric. In this paper, for simplicity we consider $p_i \geq p_j$ such that $\gamma \geq 1$ and γ increases as the technological capabilities of the firms become more asymmetric.

Both firms wish to acquire the knowledge base in order to attempt to create a radical innovation. This gives rise to a winner takes all game, such that the firm that creates the innovation first becomes a monopolist earning π_m. If both firms manage to create the innovation simultaneously, then each earns the duopoly Cournot-Nash profit of π_d.

[1] See Athreye, Kale and Ramani (2008) for examples of this phenomenon in the Indian pharmaceutical industry.

In the above context, the two firms *i* and *j* have the choice between four types of organization for the undertaking of the R&D project.

i. *R&D competition*: The firms do not share the R&D costs *F* or the R&D findings.

ii. *Cost sharing alliance:* The two firms agree upon a sharing arrangement for the fixed costs *F*. Since knowledge can be replicated costlessly, the two firms exploit their knowledge input separately thereafter. Thus, in a cost sharing alliance, cost savings are achieved through non-duplication of the efforts required to produce the knowledge input at the pre-competitive stage.

iii. *Information sharing alliance (also termed research joint venture in the literature)*: The firms invest in *F* separately but share their R&D findings so that the probability of creating the innovation is maximized.

iv. *R&D cartel*: The firms share both the cost *F* and the R&D findings so that there are cost economies and with their combined technological capabilities the probability of creating an innovation is maximized.

Given these three possible options for R&D cooperation, in what follows, we examine the following questions. Under what conditions will an R&D alliance be initiated by the firms? For which technological competency profiles will each kind of R&D alliance be initiated? What is the maximum degree of asymmetry between the competencies that can be tolerated under the three different kinds of R&D alliances? The answers in turn permit us to make inferences on the role of public policy to promote innovation through collaboration.

III. Results on R&D competition and R&D alliances

III (i). *R&D Competition*

In the absence of collaboration, the expected profit of any firm *i* from undertaking R&D is $\pi_i^{nc} = p_i(1-p_j)\pi_m + p_i p_j \pi_d - F$. Firm *i* can either be the only innovator and earn the monopoly profit π_m with a probability $p_i(1-p_j)$ or both firms can be successful and earn the duopoly profit π_d with a probability $p_i p_j$. Whenever firm *j* alone succeeds, firm *i* is left out of the market.

Clearly, a firm will undertake R&D investment in the first place only if it anticipates earning positive payoffs. We consider two possible situations to identify the conditions under which R&D competition will occur. First, where the firms are symmetric in terms of their technological capabilities, i.e. $\gamma = 1$ and second, assuming that firm *i* is the one with the higher technological capability, the context where technological capabilities are asymmetric with $\gamma > 1$. It can be easily shown that when $\gamma = 1$, $\pi_i^{nc} = \pi_j^{nc}$ and when $\gamma > 1$, $\pi_i^{nc} > \pi_j^{nc}$[2]. Therefore, to identify the condition under which R&D competition can occur, i.e. when both firms will invest in R&D, it is sufficient to check if the less capable firm *j* incurs R&D expenditure in each of the cases. If $\pi_j^{nc} > 0$ and firm *j* decides to incur the R&D expenditure, it must follow that firm *i* does likewise. This leads to our first proposition on the necessary conditions for R&D competition.

Proposition 1a: R&D competition under asymmetric competencies with $p = p_i \geq p_j$

If the R&D cost and returns are such that:

(i) $F \geq \dfrac{\pi_m^2}{4(\pi_m - \pi_d)} > \pi_d$, then there is no R&D competition, whatever the level of technological capabilities;

(ii) $\dfrac{\pi_m^2}{4(\pi_m - \pi_d)} > F > \pi_d$, there exists capability levels $\hat{p}, \hat{\hat{p}}$ with $\hat{p} < \dfrac{\pi_m}{2(\pi_m - \pi_d)} < \hat{\hat{p}}$, such that for $p_i = p \in (\hat{p}, \hat{\hat{p}})$ and $p_j \in (\dfrac{F}{(1-p)\pi_m + p\pi_d}, p)$ there is R&D competition. As *F* falls, the interval $(\hat{p}, \hat{\hat{p}})$ expands.

(iii) $\dfrac{\pi_m^2}{4(\pi_m - \pi_d)} > \pi_d \geq F$, there exists a capability level $\bar{p} < \dfrac{\pi_m}{2(\pi_m - \pi_d)}$, such that for all $p_i = p \in (\bar{p}, 1)$ and $p_j \in (\dfrac{F}{(1-p)\pi_m + p\pi_d}, p)$ there is R&D competition. As *F* falls, the interval $(\bar{p}, 1)$ expands.

Proposition 1b: R&D competition under symmetric capabilities with $p = p_i = p_j$

There is R&D competition only when p satisfies conditions (ii)-(iii).

---

[2] From the definitions of π_i^{nc} and π_j^{nc} it follows that $\pi_i^{nc} - \pi_j^{nc} = \pi_m\, p_j(1-p_i)\,[\dfrac{p_i(1-p_j)}{p_j(1-p_i)} - 1]$. Since $\gamma > 1$ implies $\dfrac{p_i(1-p_j)}{p_j(1-p_i)} > 1$, $\pi_i^{nc} - \pi_j^{nc} > 0$.

Proof: See the appendix.

Although the R&D expenditure is fixed and certain at F, the returns from such investment, dependent on the technological capability profile of the firms, are uncertain. Thus, from the outset, firm capabilities have to be above a minimal level in order to ensure positive returns after an outlay of F. It follows from the definition of π_i^{nc} that whenever F is invested, either a monopoly profit π_m can be gained or a loss of $(\pi_m - \pi_d)$ can be incurred and for higher capabilities of the rival, the increase in expected loss is greater than the increase in expected gain. Thus, there is R&D competition only if the technological capabilities of both the firms are sufficiently high.

Another outcome is that as the R&D investment F falls, the range of capability profiles under which R&D competition is viable expands. When the R&D investment F is low enough to be sustained even under a duopoly market, i.e. $F \leq \pi_d$, there exists a minimum capability level $\bar{p}$, such that for all $p \in (\bar{p}, 1)$ the expected return from R&D expenditure always exceeds the low value of F and R&D competition takes off. However, as the R&D outlay F increases, say to, $\pi_d < F < \frac{\pi_m^2}{4(\pi_m - \pi_d)}$, firms with low-end capabilities and high-end capabilities withdraw from the R&D competition. Within this range, as F increases, the interval of capabilities under which R&D competition occurs, $(\hat{p}, \hat{\hat{p}})$, decreases. Consequently, the scope of the R&D competition falls. When the required R&D outlays are very high, with $F \geq \frac{\pi_m^2}{4(\pi_m - \pi_d)}$, no firm can undertake R&D investment and no innovation is created.

Lastly, when firm capabilities are distinct, not only do the firms have to be efficient but they also have to be sufficiently symmetric or close in terms of technological capabilities. In fact, the proposition indicates that for any given technological capability p of the more efficient firm, the technological capability of the less efficient firm must lie in the interval $(\frac{F}{(1-p)\pi_m + p\pi_d}, p)$ for R&D competition to occur. Otherwise, the less efficient firm simply does not enter the innovation race.

In the remainder of the paper, in order to facilitate the comparison of payoffs under non-cooperation and cooperation at the R&D level, we restrict our attention in the non-cooperation case to R&D competition where F is low enough i.e. $F \leq \pi_d$ [3]. In particular, we make the following assumption for the rest of the paper[4]:

Assumption 1: The configuration of required R&D outlay F, market profits π_m, π_d, and firm capabilities p_i and p_j are such that R&D competition prevails with $F \leq \pi_d$, i.e. the conditions (iii) of proposition 1a hold.

From proposition 1, it follows that assumption 1 ensures that both firms are capable of undertaking R&D investment under non-collaboration anticipating payoffs of $\pi_i^{nc} > 0$ and $\pi_j^{nc} > 0$ respectively. Hence, non-collaboration at the R&D level will be tantamount to the prevalence of R&D competition and this organizational mode is the default option if collaboration does not take off.

III(ii). *The Cost Sharing Alliance*

The benefit of a cost sharing alliance is that the fixed cost F can be shared between the firms, say as αF for firm i, and $(1-\alpha)F$ for firm j, where $\alpha \in (0,1)$. Cost savings are achieved through non-duplication of efforts required to produce the knowledge input at the pre-competitive stage, but the probability of success at the development stage remains unchanged. Let us represent the payoff from a cost sharing alliance for the ith firm and the jth firm by the pair (π_i^c, π_j^c). Then by the above argument $\pi_i^c = p_i(1-p_j)\pi_m + p_i p_j \pi_d - \alpha F$ and $\pi_j^c = p_j(1-p_i)\pi_m + p_i p_j \pi_d - (1-\alpha)F$.

In order to initiate a cost sharing alliance, the firms first negotiate over the cost sharing ratio α. A number of endogenously determined cost-sharing rules are possible. In the present context, given that it is a pure bargaining problem, the Nash bargaining solution with each

[3] In some forms of collaborations like the cost-sharing alliance and the R&D cartel as the fixed cost of producing the knowledge input gets shared, some firms which do not participate in R&D competition may turn out to be willing to participate in the collaborations. Even if we consider them, their ranking over the alternative forms of collaboration would be the same as in the case considered in the paper and the basic results would remain unchanged.

[4] Similar arguments can be applied to the case where $\pi_d < F < \frac{\pi_m^2}{4(\pi_m - \pi_d)}$ and the nature of the results remain unchanged.

firm having equal bargaining power has been considered. The disagreement payoffs are evidently the R&D competition payoffs $\pi_i^{nc} > 0$ and $\pi_j^{nc} > 0$ (under conditions of assumption 1). Then the cost-sharing ratio that will prevail at equilibrium is given by the following proposition.

Proposition 2: (i) For all configurations of costs, payoff structure and technological capabilities, at equilibrium each firm will bear 50% of the fixed costs *F*.
(ii) Whenever R&D competition is possible, a cost sharing alliance will be preferred to R&D competition.

Proof: Applying the Nash-Bargaining solution to this context, the cost sharing ratio α emerges as the ratio that maximizes the product of the net gains from bargaining for the partner firms. In other words, maximizing $[(\pi_i^c - \pi_i^{nc})(\pi_j^c - \pi_j^{nc})]$ with respect to α yields the cost sharing ratio as $\alpha = \frac{1}{2}$ for all capability configurations of the two firms.

The interesting point to note in the above exercise is that usually varying the disagreement points changes the outcome of the bargaining process, because the gains from negotiation change as the disagreement points change. However, in our case, the gains from negotiation, in terms of cost savings are totally independent of the disagreement points. Hence, the 50% share is the only ratio that satisfies the Nash bargaining solution criteria of equal sharing of surplus generated by the cost sharing alliance. With this ratio, the equilibrium payoff of the firms in the cost-sharing collaboration becomes:

$$\pi_i^c = p_i(1-p_j)\pi_m + p_i p_j \pi_d - \tfrac{1}{2}F \text{ and } \pi_j^c = p_j(1-p_i)\pi_m + p_i p_j \pi_d - \tfrac{1}{2}F .$$

Clearly, the two firms will participate in a cost sharing alliance only if they earn more than under R&D competition or the following participation constraints are satisfied:

(1) $\pi_i^c > \pi_i^{nc}$.

(2) $\pi_j^c > \pi_j^{nc}$.

From the definitions of π_i^c, π_j^c, π_i^{nc} and π_j^{nc} it follows that inequalities (1) and (2) will hold if and only if the following inequalities hold:

(3) $(1-\alpha)F > 0$.

(4) $\alpha F > 0$.

It can be easily observed that at equilibrium, with $\alpha = \frac{1}{2}$, whatever the technological capabilities of the firms, under the conditions of our assumption, the participation constraints given by inequalities (3) and (4) are satisfied for both the firms.

III(iii). *The Information Sharing Alliance*

In an information sharing alliance, R&D findings are shared, which means that if one of the firms discovers the new product, in no time the other firm can launch an almost identical product at the market. Thus, the new product can be launched if either of the two firms makes the discovery. Sharing of information at the development stage reduces the probability of failure in R&D, as the technological capability of the research joint venture becomes $1-(1-p_i)(1-p_j) = p_i(1-p_j) + p_i p_j + p_j(1-p_i)$, which is greater than either of the individual capabilities of the two firms p_i or p_j. However, if successful, both the firms will launch the innovation jointly in the market earning the duopoly profit, π_d. Thus, for any firm *i*, the expected profit from an information sharing alliance is $\pi_i^i = (1-(1-p_i)(1-p_j))\pi_d - F$. Again, an information sharing alliance will be formed only if both the firms can earn more than they could obtain under non-collaboration or R&D competition, i.e. if and only if the respective participation constraints given by $\pi_i^i > \pi_i^{nc}$ and $\pi_j^i > \pi_j^{nc}$ are satisfied:

(5) $p_i(1-p_j)(\pi_m - \pi_d) - p_j(1-p_i)\pi_d < 0$.

(6) $p_i(1-p_j)(\pi_m - \pi_d) - p_j(1-p_i)\pi_d + p_j(1-p_i)\ [1 - \frac{p_i(1-p_j)}{p_j(1-p_i)}] < 0.$

Under which capability configurations will the above two conditions be satisfied? This is revealed in the next proposition.

Proposition 3: Whatever the configuration of technological capabilities of the two firms, an information sharing alliance will never be formed.

Proof: See the appendix.

The intuition behind proposition 3 is as follows. Each firm considers the possibility of sharing information to insure itself against being thrown out of the market, in case its rival creates the innovation while it does not. However, there is a price for this option. By sharing information both firms reduce their chance of failure in the R&D competition, but by doing so they also completely forego the chance to capture the monopoly rent π_m. Information sharing leads to launching almost identical products at the market almost at the same time whereby each firm earns the duopoly profit π_d. From standard oligopoly theory we know $\pi_m > 2\pi_d > \pi_d$. Therefore, if the firms are symmetric i.e. no one has advantage over the other in R&D, for individual firms the opportunity cost of missing out on monopoly rent turns out to be greater than the expected profit from participation in the alliance even though the probability of failure reduces with the alliance, and hence, the alliance is not formed.

When the firms are asymmetric, the non-formation of an information alliance can be explained similarly. The more capable firm is dissuaded from entering into an alliance because its probability to succeed is higher and it sees no point in foregoing the monopoly rent by forming an alliance that could lower its profit drastically. The inefficient firm in this situation facing the odds against its success in the R&D competition, may be willing to participate in the alliance as it provides an insurance against exclusion from the monopoly rent which is imminent, but its proposal is declined by the more capable firm. Therefore, in this case also, the information sharing alliance is not formed.

III(iv). *The R&D Cartel*

In an R&D cartel, with both cost and information sharing, the expected payoffs of the firms i and j are: $\pi_i^r = (1-(1-p_i).(1-p_j))\pi_d - \alpha F$ and $\pi_j^r = (1-(1-p_i).(1-p_j))\pi_d - (1-\alpha)F$ respectively. Furthermore, in the bargaining on cost sharing, the disagreement payoffs are $\pi_i^{nc} > 0$, $\pi_j^{nc} > 0$ as in the earlier two cases and the Nash Bargaining solution[5] α^* emerges as :

[5] Similar to the cost sharing cartel here also we assign equal bargaining power to the firms. When $\frac{1}{2} - \frac{\pi_m(p_i - p_j)}{2F}$ is negative then the R&D outlay will be entirely borne by the less efficient firm j.

(7) $\alpha^* = Max\left\{0, \frac{1}{2} - \frac{\pi_m(p_i - p_j)}{2F}\right\}$

The R&D cartel will be preferred over R&D competition, if and only if at α^*, the participation constraint of the ith firm, $\pi_i^r > \pi_i^{nc}$, and that of the jth firm, $\pi_j^r > \pi_j^{nc}$, are satisfied. In other words, an R&D cartel is formed if and only if the following inequality holds:

(8) $F > (p_i + p_j - 2\, p_i\, p_j)(\pi_m - 2\pi_d)$.

Since $\pi_m > 2\,\pi_d$, and $p_i + p_j - 2\, p_i\, p_j = [p_i\,(1-p_j) + p_j\,(1-p_i)] > 0$, the right hand side of inequality (8) is positive. Moreover, we can simplify inequality (8) by assuming $F = \beta\pi_d$ where $\beta \in (0, 1]$ and rewrite the participation constraint as follows:

(9) $\beta\pi_d > (p_i + p_j - 2p_i p_j)(\pi_m - 2\pi_d)$.

Now, we can present the criteria for the formation of an R&D cartel as follows.

Proposition 4:

(i) An R&D cartel will always be preferred to R&D competition if the R&D outlay, F, is greater than the opportunity cost of forming an R&D cartel, $(\pi_m - 2\,\pi_d)$,or for high values of β, whatever the degree of asymmetry.

(ii) When $F < (\pi_m - 2\,\pi_d)$ an R&D cartel will be initiated always if firms have very high technological capabilities and limited asymmetry. However, for very small F or very low values of β, an R&D cartel may also be formed if firms have low technological capabilities with limited asymmetry.

Proof: See the appendix for formal presentation of proposition and the proof.

The intuition behind the first part of the above proposition is as follows. If the fixed cost of R&D is high and the monopoly profit to be earned from the development of the new product is low, the opportunity cost of forfeiting the monopoly profit is low, while the benefit from sharing of the fixed cost of the knowledge input is high. Hence, an R&D cartel is more attractive. However, for higher monopoly profit, the cost of information sharing may outweigh the benefit of cost sharing, and therefore, participation in the R&D cartel may turn out to be an unattractive option depending on the configuration of firm capabilities. For instance, if firm capabilities are not high, by sharing information, they do not lose much, as the probability of new discovery on their own is fairly low, and furthermore if the fixed cost of R&D is high, the benefit of cost sharing is also high. Therefore, low capability firms will prefer an R&D cartel under these conditions. On the other hand, if the firms are highly capable (i.e. p is in the neighbourhood of 1), in the absence of information sharing, an individual firm fears market exclusion as its rival could succeed with a high probability. Here participation in the R&D cartel provides insurance against possible market exclusion, and benefits from cost sharing exceed the lowering of innovation rent due to information sharing, leading firms to initiate an R&D cartel.

The second part of the proposition indicates that if the technological capability of the relatively efficient firm itself is low and the asymmetry is limited, then the firms will form an R&D cartel. Other than the cost sharing advantage, an R&D cartel permits the relatively inefficient firm to increase its chances of success by collaborating with the more efficient firm. On the other hand, the more capable firm, not being too efficient itself does not lose much by sharing its R&D findings with the partner firm as this is compensated by gains from the cost sharing. Again, if both firms are very capable, then they initiate an R&D cartel to avoid market exclusion in the post-innovation period.

In contrast to this, as asymmetry increases, the less capable firm is always willing to join the R&D cartel as it benefits from sharing information (and is otherwise likely to lose out in R&D competition), but the more capable firm may not agree so easily. The more capable firm knows that even if it does not join the R&D cartel and does not share the information, it will not lose much since the probability of its rival discovering the product is low and consequently its risk of market exclusion is also low. Therefore, an R&D cartel is not formed.

The intuition described above is also illustrated in the following simulations.

[Insert table 1 here]

Table 1 presents simulations corresponding to a context where $F < \pi_m - 2\pi_d$. As can be seen, for high and low capability profiles of both firms, as long as asymmetry is limited, an R&D cartel dominates non-cooperation. However, there are capability profiles, that are in the middle (p_i=0.55 and p_j=0.3) when an R&D cartel cannot be formed because the more capable firm prefers to compete alone. It can also be noticed that for low capabilities, the *j*th firm cannot engage in R&D competition and therefore such cases are not considered for comparison.

III(v). *Firm choice among the R&D alliances*

So far we have compared the returns from each of the three forms of R&D cooperation with R&D competition and identified the conditions under which cooperation will dominate competition. Now, let us consider the case when the two firms come together to choose between R&D competition and the three forms of R&D cooperation. From propositions 1-4, we know that the choice will lie essentially between an R&D cartel and a cost sharing alliance. In fact, whenever the R&D cartel is possible, the cost sharing alliance is also possible, though the converse need not be true. This leads us to the question: If both an R&D cartel and a cost sharing alliance are possible for a firm, which would be preferred? We answer this question in the next proposition.

Proposition 5: Given the choice between the formation of the R&D cartel and the cost sharing alliance, if the firms are not too asymmetric in terms of their technological capability, the cost sharing alliance will be preferred to the R&D cartel. If the firms are very asymmetric, then the less capable firm may prefer the R&D cartel to the cost sharing alliance, while the more capable firm will prefers the opposite. In this case no alliance will be formed[6].

Proof: See the appendix.

The intuition behind the proposition is not difficult to understand. As we discussed earlier, information sharing in the R&D cartel comes with a price tag, especially for the firm which is more capable. Therefore, the more capable firm will prefer the cost sharing alliance rather than an information sharing alliance. In contrast, participation in the cost sharing alliance involves only pure benefit to both firms. Therefore, whenever the asymmetry between the firms is not very high, the less capable firm will also agree to the cost sharing alliance if it is the only option desired by the more capable firm. However, if the technological capability of one of the firms is very low, then in a R&D cartel, it benefits from both information sharing and cost sharing and is its preferred choice. In this case, the more

[6] In this model we have assigned equal bargaining power to all types of firm. In this situation, clearly, had the more inefficient firm have the greater bargaining power the R&D cartel would have been preferred to the cost sharing alliance.

capable firm, which always prefers a cost sharing alliance to an R&D cartel will have an opposite preference. Hence, no alliance will be formed and the two firms will continue to compete with each other as they were doing in the first place.

The proposition is also illustrated by the simulations given in table 2.

[insert table 2]

It can be noted from table 2, that for the given configuration, when both the firm are equally highly capable, they prefer to initiate a cost sharing alliance. However, when there is significant asymmetry the more capable firm gains more from a cost sharing alliance, while the less capable firm prefers an R&D cartel. If both firms have equal bargaining powers, in this case, no alliance is likely to be initiated.

III(vi) *Ranking according to Social Welfare*

There is a widespread acceptance that the State should encourage innovation through promoting cooperation between firms at the R&D level. In this case, which kind of R&D alliance should be promoted? In other words, can we rank the alternative R&D collaborations that private firms can form between themselves, in terms of the social welfare generated? How do the social benefits from the initiation of the three R&D alliances compare with that from R&D competition? In this section we try to find out answers to these questions.

Suppose, the social surplus (defined as the sum of the consumer and the firms' surplus) is given by s_m if a monopoly is created in the market for the new product. Similarly, if a duopoly is created, the social surplus is given by s_d. From standard oligopoly theory we know that it is always the case that $s_d > s_m$. The expected social surplus of the society from the R&D competition is given by

$$S_{nc} = p_i(1-p_j)s_m + p_j(1-p_i)s_m + p_i p_j s_d - 2F .$$

Furthermore, the social surplus from the cost sharing alliance, the information sharing alliance and the R&D cartel are respectively given by:

$$S_c = p_i(1-p_j)s_m + p_j(1-p_i)s_m + p_i p_j s_d - F ;$$

$$S_i = p_i(1-p_j)s_d + p_j(1-p_i)s_d + p_i p_j s_d - 2F ; \text{ and:}$$

$$S_r = p_i(1-p_j)s_d + p_j(1-p_i)s_d + p_i p_j s_d - F .$$

Proposition 6: From the social welfare point of view, the R&D cartel is preferable to both the cost sharing alliance and the information sharing alliance. Furthermore, having any form of R&D alliance is better than R&D competition.
Proof: See the appendix.

Society prefers any of the three types of R&D alliances to R&D competition for either one or both of the following reasons: unlike in R&D competition, an R&D alliance eliminates duplication of fixed costs to acquire the knowledge input and any form of R&D cooperation creates a duopoly market for the innovation with a higher probability.

Furthermore, from the social welfare point of view, the R&D cartel is preferable to the information sharing alliance because it prevents the duplication of the fixed cost of acquiring the knowledge input while yielding the same benefits (or costs) from information sharing. Similarly, even though the cost sharing rule is different in the cost sharing alliance and the R&D cartel, the nature of the cost sharing benefits generated by the two alliances is the same and in addition, in the R&D cartel, firms and society benefit from the sharing of R&D findings. Therefore, the R&D cartel is preferred to either of the two alternative forms of alliances.

IV. Conclusions

In a comprehensive survey of R&D collaboration, Veugelers [1998] insists that incentives for cooperation among asymmetric firms must be studied more because "Although the empirical analysis provides massive evidence of asymmetries between partners, the theoretical work has mostly concentrated on alliances between symmetric firms". In particular, firms are assumed to have the same technological capabilities, which eliminates the need to examine one of the fundamental problems of R&D cooperation, namely that of "appropriate partner selection". Thus, in an attempt to contribute to a better understanding of R&D cooperation between asymmetric firms, this paper considered duopolistic firms of non-identical technological competencies and examined the incentives for the formation of different kinds of R&D alliances. Firms had the option of either engaging in R&D competition or initiating an information sharing alliance, a cost sharing alliance or an R&D cartel. A set of propositions were derived comparing the profit accrued by firms from R&D competition and the three different kinds of R&D alliances. Then they were also ranked in terms of the social welfare generated. The results highlighted the role of firm-specific technological capability in the choice of form of R&D cooperation and demonstrated that a high degree of asymmetry deters firms from entering into R&D alliances.

The paper also yields some managerial guidelines for the initiation of R&D alliances. First, it advocates that an information sharing alliance should never be formed unless there are other public benefits, such as subvention from the government, or reputational benefits in terms of corporate social responsibility. Second, if the firms are not too asymmetric in terms of technological capabilities, a cost sharing alliance can be initiated as it will benefit both firms. Third, if the firms are very asymmetric, then it is better to continue with R&D competition as there is likely to be a conflict of preferences over of choice of R&D alliance, with the less capable firm favouring an R&D cartel and the more capable firm preferring the cost sharing alliance.

Three policy inferences can also be made on the basis of the results of the paper. First, unlike in the case of symmetric firms, firm differences in technological capabilities can lead to contradictions between private and public rationality when it comes to choice of type of R&D alliance. While the model confirms one of the main results of the existing literature on R&D alliances, that all three forms of alliances yield greater social welfare than R&D competition between firms and the R&D cartel is unambiguously the best for society, it shows that such a choice need not be the preferred option of all firms.

The above contradiction is most likely to occur if the competing firms are very asymmetric. In this case, the government should provide them with incentives to engage in cooperation because otherwise no alliance may be formed, which is not in the interests of society. For instance, there can be publicly funded R&D programs that require a joint research proposal drafted by a set of asymmetric collaborating organizations as a pre-requisite to obtaining funds. Pure information research consortiums can be promoted to generate innovations for life threatening problems like medicines for HIV/AIDS or malaria in the name of corporate social responsibility, which otherwise would not be initiated. Subventions could be provided for the creation of science and technology parks, which often facilitate the sharing of fixed costs of R&D investment necessary for innovation creation.

Third, if the firms are sufficiently symmetric, they will form cost sharing alliance on their own. But, it is in the interests of society that the government ensures information sharing along with cost sharing. Here policies like tax benefits or access to infrastructural facilities to organizations in private technology parks in return for regularly sharing information among themselves via meetings and conferences can be considered.

Finally, some empirical and theoretical extensions of the present paper can be envisaged. Two testable hypotheses that emerge from the paper are: (i) outside of technology parks, R&D alliances are more likely to be initiated among firms of similar technological capabilities; and (ii) among the different forms of R&D cooperation, the most prevalent will involve cost-sharing alone, followed by cost and information sharing and rarely pure information sharing. Theoretical extensions of the present paper that can also be considered are inclusion of variable R&D investment, spillovers and incremental quality enhancing innovations. Another possibility is to adapt the model to include other agents besides just competing firms. For instance, R&D cooperation in the high-tech sectors often involves public organizations as well as firms and cooperation can also be initiated between firms occupying different positions in the vertical product value chain (Belderbos et al. 2004a, 2004b).

References

Athreya, S., Kale, D. and Ramani, S. V., 2008, Experimentation with Strategy and the Evolution of Dynamic Capability in the Indian Pharmaceutical Sector, Working Paper ALISS-INRA.

Belderbos, R., Carree, M., Diederen, B., Lokshin, B. and Veugelers, R., 2004, 'Heterogeneity in R&D Cooperation Strategies,' *International Journal of Industrial Organisation*, 22, pp.1237-63.

Belderbos, R., Carree, M. and Lokshin, B., 2004, 'Cooperative R&D and Firm Performance,' *Research Policy*, 33, pp.1477-92.

Bhattacharya, S., Glazer, J. and Sappington, D., 1992, 'Licensing and the Sharing of Knowledge in Research Joint Ventures,' *Journal of Economic Theory*, 56, pp.43-69.

Cabon-Dhersin, M. L. and Ramani, S. V., 2004, 'Does Trust Matter for R&D Cooperation ? A Game Theoretic Examination,' *Theory and Decision*, 57, pp.143-80.

Caloghirou, Y., Ioannides, S. and Vonortas, N., 2003, 'Research Joint Ventures,' *Journal of Economic Surveys*, 17, pp.541-69.

Chaudhuri, P., 1995, 'Technological Asymmetry and Joint Product Development,' *International Journal of Industrial Organisation*, 13, pp.23-39.

D'Aspremont, C. and Jacquemin, A., 1988, 'Cooperative and Non-Cooperative R & D in Duopoly with Spillovers,' *American Economic Review*, 78, pp.1133 -37.

de Man, A.-P. and Duysters, G., 2005, 'Collaboration and Innovation: A Review of the Effects of Mergers, Acquisitions and Alliances on Innovation,' *Technovation*, 25, pp.1377-87.

Gandal, N. and Scotchmer, S., 1993, 'Coordinating Research through Research Joint Venture,' *Journal of Public Economics*, 51, pp.173-93.

Kamien, M., I. and Zang, I., 2000, 'Meet Me Halfway: Research Joint Ventures and Absorptive Capacity,' *International Journal of Industrial Organisation*, 18, pp.995-1012.

Kamien, M., Muller, I. and Zang, I., 1992, 'Research Joint Ventures and R & D Cartels,' *American Economic Review*, 82, pp.1293 - 306.

Katz, M., 1986, 'An Analysis of Cooperative Research and Development,' *Rand Journal of Economics*, 17, pp.527 - 43.

Lopez, A., 2008, 'Determinants of R&D Cooperation: Evidence from Spanish Manufacturing Firms,' *International Journal of Industrial Organisation*, 26, pp.113-36.

Mills, D. and Smith, W., 1996, 'It Pays to Be Different, Endogenous Heterogeneity of Firms in an Oligopoly,' *International Journal of Industrial Organization*, 14, pp.317-29.

Miotti, L. and Sachwald, F., 2003, 'Co-Operative R&D: Why and with Whom? An Integrated Framework Analysis,' *Research Policy*, 32, pp.1481-99.

Morash, K., 1995, 'Moral Hazard and Optimal Contract Form for R&D Cooperation,' *Journal of Economic Behavior and Organization*, 28, pp.63-78.

Penrose, E. T., 1959, *The Theory of the Growth of the Firm*, (John Wiley, New York).

Pérez-castrillo, J., D. and Sandonis, J., 1997, 'Disclosure of Know How in Research Joint Venture,' *International Journal of Industrial Organization*, 15, pp.51-75.

Petit, M. L. and Tolwinski, B., 1999, 'R&D Cooperation or Competition?,' *European Economic Review*, 43, pp.185-208.

Poyago-Theotoky, J., 1997, 'Research Joint Ventures and Product Innovation: Some Welfare Aspects,' *Economics of Innovation and New Technology*, 5, pp.51-73.

Röller, L.-H., Siebert, R. and Tombak, M. M., 2007, 'Why Firms Form (or Do Not Form) Rjvs,' *The Economic Journal*, 117, pp.1122-44.

Sena, V., 2004, 'The Return of the Prince of Denmark: A Survey on Recent Developments in the Economics of Innovation,' *The Economic Journal*, 114, pp.312-32.

Van Long, N. and Soubeyran, A., 1999, 'Asymmetric Contributions to Research Joint Ventures,' *The Japanese Economic Review*, 50, pp.122-37.

Veugelers, R., 1998, 'Collaborative in R&D: An Assessment of Theoretical and Empirical Findings,' *De Economist*, 146, pp.419-43.

Veugelers, R. and Kesteloot, K., 1996, 'Bargained Shares in Joint Ventures among Asymmetric Partners: Is the Matthew Effect Catalyzing?,' *Journal of Economics*, 64, pp.23-51.

Appendix

Proof of proposition 1a.

Suppose, $\gamma > 1$ i.e. $p = p_i > p_j$, then $\pi_i^{nc} > \pi_j^{nc}$. Therefore, both firms enter into R&D competition if and only if $\pi_j^{nc} > 0$. From the definition of π_j^{nc}, it follows that this occurs if and only if :

(A.1) $$p_j \in \left(\frac{F}{(1-p)\pi_m + p\pi_d}, p\right).$$

Furthermore, the given interval is non-empty only if $\frac{F}{(1-p)\pi_m + p\pi_d} < p$, which in turn implies:

(A.2) $$f(p) = p^2 - \left(\frac{\pi_m}{\pi_m - \pi_d}\right)p + \frac{F}{\pi_m - \pi_d} < 0.$$

Observe that $f(p)$ is a continuous function over $p \in (0, 1)$. As $p \to 0$, $f(p) \to f(0) = \frac{F}{\pi_m - \pi_d} > 0$ and as $p \to 1$, $f(p) \to f(1) = \frac{F - \pi_d}{\pi_m - \pi_d}$. Since $\pi_m > \pi_d$, $\frac{F}{\pi_m - \pi_d} > 0$ and $\frac{F - \pi_d}{\pi_m - \pi_d} >=< 0$ if and only if $F >=< \pi_d$.

The function $f(p)$ attains its minimum at $p_{\min} = \frac{\pi_m}{2(\pi_m - \pi_d)}$ and $f(p_{\min}) = \frac{4F(\pi_m - \pi_d) - \pi_m^2}{4(\pi_m - \pi_d)^2}$. Clearly, $f(p_{\min}) >=< 0$ if and only if $F >=< \frac{\pi_m^2}{4(\pi_m - \pi_d)}$. Again, since $\pi_m > \pi_d$, it can be easily shown that $\frac{\pi_m^2}{4(\pi_m - \pi_d)} > \pi_d$.

Now we can check for R&D competition in three possible cases of R&D investment and profit configurations.

(i): $F \geq \frac{\pi_m^2}{4(\pi_m - \pi_d)} > \pi_d$. Here $f(p_{\min}) \geq 0$ and $f(1) > 0$. Furthermore, since $f(0) > 0$ always, the condition (A.2) is never satisfied for any technological capability $p \in (0, 1)$.

(ii): $\frac{\pi_m^{\ 2}}{4(\pi_m - \pi_d)} > F > \pi_d$. Here *f(0)>0,* $f(p_{\min}) < 0$ and $f(1) > 0$. Since *f(p)* is a continuous function over $p \in (0,\ 1)$, there exists two capability values, $\hat{p}$ and $\hat{\hat{p}}$ in the interval (0,1) such that $\hat{p} < p_{\min} \leq \hat{\hat{p}}$ and for all $p \in (\hat{p}, \hat{\hat{p}})$ the condition (A.2) holds. Furthermore, if condition A.1 holds, i.e. firm *j* is also competent enough to undertake R&D investment given the presence of firm *i*, there is R&D competition.

(iii): $\frac{\pi_m^{\ 2}}{4(\pi_m - \pi_d)} > \pi_d \geq F$. Here *f(0)>0,* $f(p_{\min}) < 0$ and $f(1) \leq 0$. Again, since *f(p)* is a continuous function over $p \in (0,\ 1)$, there exists a value, $\overline{p}$ such that $p_{\min} < \overline{p} \leq 1$ and for all $p \in (\overline{p}, 1)$ the condition (A.2) holds. Furthermore, if condition A.1 holds also there is R&D competition.

Proof of proposition 1b.

If $\gamma = 1$, then $\pi_i^{nc} = \pi_j^{nc} = \pi$ and the firms engage in R&D competition if and only if $\pi > 0$ or *f(p)* < 0. The derivation of the conditions under which *f(p)* < 0 are exactly the same as that in the proof of 1a above and the statement of the second part of the proposition follows.

Proof of proposition 3. Suppose, $p_i(1-p_j)(\pi_m - \pi_d) - p_j(1-p_i)\pi_d = \overline{\pi}$. Then the participation constraints given by inequalities (5) and (6) can be written as:

(A.3) $\overline{\pi} < 0$

(A.4) $\overline{\pi} + p_j(1-p_i)\ [1 - \frac{p_i(1-p_j)}{p_j(1-p_i)}] < 0$

When the firms are symmetric, i.e. $p_i = p_j = p$, the two inequalities (A.3) and (A.4) are identical following $\frac{p_i(1-p_j)}{p_j(1-p_i)} = 1$. Moreover from standard oligopoly theory we know that $\pi_m > 2\pi_d$ and hence $\overline{\pi} = p(1-p)(\pi_m - 2\pi_d) > 0$. Therefore, the inequality (A.3) can never hold.

When the firms are asymmetric with $p_j < p_i = p$ we have $\frac{p_i(1-p_j)}{p_j(1-p_i)} > 1$ (refer to footnote 3). This means that $\overline{\pi}$ can be written alternatively as:

(A.5) $\bar{\pi} = p_j(1-p_i)\left[\frac{p_i(1-p_j)}{p_j(1-p_i)}(\pi_m-\pi_d) - \pi_d\right]$.

Again given that $\pi_m > 2\pi_d$ and $\frac{p_i(1-p_j)}{p_j(1-p_i)} > 1$ we have $\bar{\pi} > 0$ and in this case also inequality (A.3) can never hold. Therefore, the statement of the proposition follows.

Proof of proposition 4.

Recall that when firms are symmetric with $p_i = p_j = p$, there exists a minimum capability level, say $\bar{p}$, such that $f(\bar{p}) = 0$ and for all $p \in (\bar{p},1)$, $f(p) < 0$ making R&D competition possible.

In this interval $(\bar{p},1)$ are there any capability levels under which an R&D cartel will be preferred ? To answer this question, we start by noting that an R&D cartel dominates an R&D competition whenever inequality (8) is satisfied along with assumption 1. Then, we simplify inequality (8) by assuming $F = \beta\pi_d$ where $\beta \in (0, 1]$ and rewrite the participation constraint as $\beta\pi_d > (p_i + p_j - 2p_i p_j)(\pi_m - 2\pi_d)$. When $p_i = p_j = p$, the preceding inequality is transformed into:

$$p^2 - p + \frac{\beta\pi_d}{2(\pi_m - 2\pi_d)} > 0.$$

Defining $\phi(p) = p^2 - p + \frac{\beta\pi_d}{2(\pi_m - 2\pi_d)}$, the condition for participation in the R&D cartel in inequality (9) can then be rewritten as:

(A.6) $\phi(p) > 0$.

The function $\phi(p)$ is continuous over $p \in (\bar{p},1)$ and reaches its minimum at $p = \frac{1}{2}$ with $\phi\left(\frac{1}{2}\right) = -\frac{1}{4} + \frac{\beta\pi_d}{2(\pi_m - 2\pi_d)}$. Furthermore it can be easily noted that , $\phi\left(\frac{1}{2}\right) > = < 0$ if and only if $2\pi_d(1 + \beta) > = < \pi_m$ or $2F > = < \pi_m - 2\pi_d$. We will now examine the case of high costs and low costs seperately.

Case 1: When $2F \geq \pi_m - 2\pi_d$, or β is high, then $\phi\left(\frac{1}{2}\right) \geq 0$. Second, since $\phi(0) > 0$, $\phi(1) > 0$ and $\phi(p)$ is a continuous function, it implies that $\phi(p) > 0$ for all p. Consequently, for any given configuration F, π_m and π_d, there exists a minimum capability level, $\bar{p}$ such that in the symmetric case, R&D competition is viable for all capabilities *p*, such that $p \in (\bar{p}, 1)$ and in the asymmetric case, R&D competition is viable for all $p_i = p \in (\bar{p}, 1)$ and $p_j \in (\frac{F}{(1-p)\pi_m + p\pi_d}, p)$. Finally, since $\phi(p) > 0$ for all $p \in (0,1)$, it is the also the case that $\phi(p) > 0$ over the corresponding domains where R&D competition is possible in the symmetric and asymmetric cases. Hence, whenever R&D competition is viable it will be rejected in favour of an R&D cartel.

Case 2: When $2F < \pi_m - 2\pi_d$ or β is low, then $\phi\left(\frac{1}{2}\right) < 0$. This is because the position of the $\phi(p)$ function in the $(p, \phi(p))$ space depends on the value of β and as the value of β decreases, the function shifts down. Furthermore, since $\phi(p)$ is a quadratic function, it will cut the X-axis at two points say p_1 and p_2 with $p_1 < \frac{1}{2} < p_2$ as shown in figure 1. Similarly the function *f(p)* depends on the value of the R&D outlay *F*, and as *F* decreases, the function *f(p)* shifts down. This means for higher values of *F*, the function *f(p)* will intersect function $\phi(p)$ but for lower values of *F*, the function *f(p)* will be entirely to the left of function $\phi(p)$. In the former case $\bar{p} > p_1$ and in the latter case $\bar{p} < p_1$ as shown in figure 1.

[insert figure 1 here]

When $\bar{p} > p_1$, it means that for all *p*, such that $1 \geq p \geq \max\{\bar{p}, p_2\}$, $f(p) \leq 0$ and $\phi(p) \geq 0$. In other words in this region of high technological capabilities, in the neighbourhood of 1, R&D competition will be possible but an R&D cartel will be even better.

When $\bar{p} < p_1$, there will be two neighbourhoods in which $f(p) \leq 0$ and $\phi(p) \geq 0$. First, there will be a neighbourhood around $\bar{p}$, containing lower capabilities *p* such that $\bar{p} \leq p \leq p_1$ in which an R&D cartel will dominate R&D competition. Second, there is a neighbourhood of high capabilities *p*, such that $1 \geq p \geq \max\{\bar{p}, p_2\}$, where again both the required conditions will be satisfied.

This completes the symmetric case.

Coming to asymmetric capabilities, recall that for R&D competition we must have for all $p_j < p_i$, $p_i = p \in (\bar{p},1)$ and $p_j \in \left(\frac{\beta\pi_d}{(1-p)\pi_m + p\pi_d}, p \right)$. Again recall that an R&D cartel will be preferred to R&D competition, if inequality (9) is satisfied. Now when $p_j = p_i$, inequality (9) is the same as condition (A.6). Therefore, by continuity of all functions concerned, and by the arguments described above for the symmetric case, there exists an open neighbourhood around $p_j = p_i = 1$ where an R&D cartel will dominate R&D competition and in the case of low values of *F*, an open neighourhood around $p_j = p_i = \bar{p}$ where an R&D cartel will dominate R&D competition.

Proof of proposition 5.

Contrary to the statement of the proposition, suppose that the *i*th firm and the *j*th firm prefer the R&D cartel to a cost sharing alliance or are indifferent between them, when both are possible.

Then, at the equilibrium cost sharing ratio, α*, the following inequality must hold for the ith firm:

(A.7) $\pi_i^r \geq \pi_i^c$

Using the definitions of π_i^r and π_i^c, and substituting the respective values of α* in them, inequality (A.8) becomes:

(A.8) $[p_i(1-p_j) + p_j(1-p_i)](2\pi_d - \pi_m) \geq 0$.

Since $\pi_m > 2\pi_d$ and $[p_i(1-p_j) + p_j(1-p_i)] > 0$, inequality (A.8) can never be true. Therefore, the converse must be true. It must be the case that the more technologically capable, *i*th firm, prefers the cost sharing alliance to the R&D cartel, irrespective of the degree of asymmetry.

Similarly, if the less capable *j*th firm prefers the R&D cartel to the cost sharing alliance, the following inequality must hold at the equilibrium cost sharing ratio, α*:

(A.9) $\pi_j^r \geq \pi_j^c$

Using the definitions of π_j^r and π_j^c and substituting the respective values of α* in them, inequality (A.9) can be written as:

(A.10) $$\bar{\pi} + p_j(1-p_i)[1-\frac{p_i(1-p_j)}{p_j(1-p_i)}] + \frac{\pi_m(p_i - p_j)}{2} \leq 0.$$

Clearly, if the firms are perfectly symmetric, then inequality (A.10) will not hold, since $\bar{\pi} > 0$. Thus, if the jth firm is not too inefficient (or too asymmetric vis-à-vis firm *i*), it will prefer the cost sharing alliance to the R&D cartel. But, since as asymmetry increases, and the term $\frac{p_i(1-p_j)}{p_j(1-p_i)}$ becomes increasingly greater than 1, there is a possibility that inequality (A.10) may hold and thus the statement of the proposition follows.

Proof of proposition 6.

It follows clearly from the definitions that $S_r > S_i$. Therefore, the society prefers the R&D cartel to the information sharing alliance.

Comparing S_r and S_c it can be shown that:

(A.11) $$S_r - S_i = [p_i(1-p_j) + p_j(1-p_i)](S_d - S_m)$$

Since $S_d > S_m$ and $p_i(1-p_j) + p_j(1-p_i) > 0$, from (A.11) it follows that $S_r > S_c$. Therefore, the statement in the first part of the proposition follows.

On the other hand, it can be seen from the definitions that since $S_d > S_m$, S_{nc} is smaller than either of S_c, S_i or S_r. Therefore, the statement of the second part of the proposition follows.

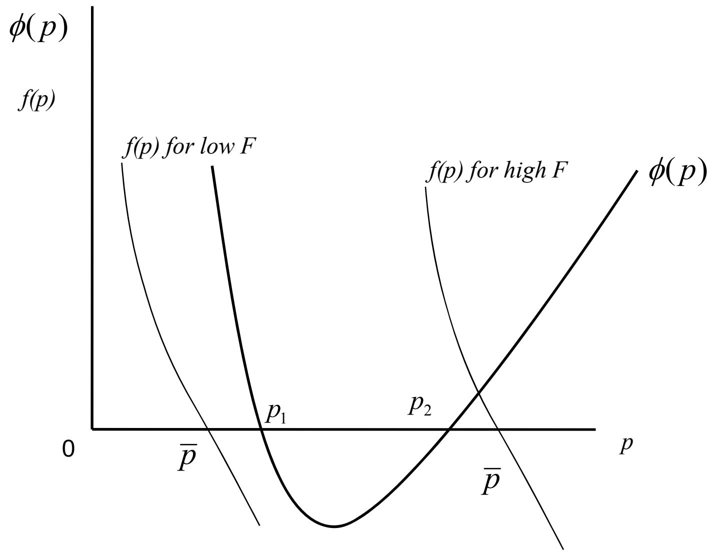

Figure 1 : Functions $\phi(p)$ and *f(p)*

F	p_i	p_j	c_i	c_j	π_i^{nc}	π_j^{nc}	π_i^r	π_j^r
50	0.9	0.9	25	25	58	58	74	74
50	0.9	0.8	10	40	76	46	88	58
50	0.9	0.5	0	50	130	10	95	45
50	0.9	0.3			166	-14		
50	0.3	0.25	17.5	32.5	25	10	30	15
50	0.3	0.2			28	-2		
50	0.55	0.3	0	50	82	7	68.5	18.5
50	0.5	0.5	50	50	25	25	50	50

$\pi^m = 300$; $\pi^d = 100$;

Table 1

Profit under non-cooperation and R&D cartel

p_i	p_j	π_i^{nc}	π_j^{nc}	c_i	c_j	α	π_i^i	π_j^i	π_i^c	π_j^c	π_i^r	π_j^r
0.90	0.90	58.00	58.00	25.00	25.00	0.50	49.00	49.00	83.00	83.00	74.00	74.00
0.90	0.50	130.00	10.00	0.00	50.00	0.00	45.00	45.00	155.00	35.00	95.00	45.00
0.90	0.30	166.00	-14.00									

$\pi^m = 300$; $\pi^d = 100$; $F = 50$

Table 2

Profit under non-cooperation and R&D cooperation

Dresden Discussion Paper Series in Economics

04/07 **Lehmann-Waffenschmidt, Marco / Hain, Cornelia:** Neuroökonomie und Neuromarketing: Neurale Korrelate strategischer Entscheidungen

05/07 **Günther, Edeltraud / Lehmann-Waffenschmidt, Marco:** Deceleration - Revealed Preference in Society and Win-Win-Strategy for Sustainable Management

06/07 **Wahl, Jack E. / Broll, Udo:** Differential Taxation and Corporate Futures-Hedging

07/07 **Bieta, Volker / Broll, Udo / Milde, Hellmuth / Siebe, Wilfried:** The New Basel Accord and the Nature of Risk: A Game Theoretic Perspective

08/07 **Kemnitz, Alexander:** Educational Federalism and the Quality Effects of Tuition Fees

09/07 **Mukherjee, Arijit / Broll, Udo / Mukherjee, Soma:** Licensing by a Monopolist and Unionized Labour Market

10/07 **Lochner, Stefan / Broll, Udo:** German Foreign Direct Investment and Wages

11/07 **Lehmann-Waffenschmidt, Marco:** Komparative Evolutorische Analyse – Konzeption und Anwendungen

12/07 **Broll, Udo / Eckwert, Bernhard:** The Competitive Firm under Price Uncertainty: The Role of Information and Hedging

13/07 **Dittrich, Marcus:** Minimum Wages and Union Bargaining in a Dual Labour Market

14/07 **Broll, Udo / Roldán-Ponce, Antonio / Wahl, Jack E.::** Barriers to Diversification and Regional Allocation of Capital

15/07 **Morone, Andrea / Fiore, Annamaria / Sandri, Serena:** On the Absorbability of Herd Behaviour and Informational Cascades: An Experimental Analysis

16/07 **Kemnitz, Alexander:** Native Welfare Losses from High Skilled Immigration

17/07 **Hofmann, Alexander / Seitz, Helmut:** Demographiesensitivität und Nachhaltigkeit der Länder- und Kommunalfinanzen: Ein Ost-West-Vergleich

01/08 **Hirte, Georg / Brunow, Stephan:** The Age Pattern of Human Capital and Regional Productivity

02/08 **Fuchs, Michaela / Weyh, Antje:** The Determinants of Job Creation and Destruction: Plant-level Evidence for Eastern and Western Germany

03/08 **Heinzel, Christoph:** Implications of Diverging Social and Private Discount Rates for Investments in the German Power Industry. A New Case for Nuclear Energy?

04/08 **Bieta, Volker / Broll, Udo / Siebe, Wilfried:** The Banking Firm: The Role of Signaling with Collaterals

05/08 **Felder, Stefan / Werblow, Andreas:** Do the Age Profiles of Health Care Expendidure Really Steepen over Time? New Evidence from Swiss Cantons

06/08 **Broll, Udo / Wahl, Jack E. / Wessel, Christoph:** Export Production, Hedging Exchange Rate Risk: The Duopoly Case

07/08 **Choi, Jay-Pil / Thum, Marcel:** The Economics of Political-Connected Firms

08/08 **Broll, Udo / Gilroy, B. Michael / Lukas, Elmar:** Export Production under Exchange Rate Uncertainty

09/08 **Broll, Udo / Schmidt, Christian W.:** The Effect of Exchange Rate Risk on US Foreign Direct Investment: An Empirical Analysis

10/08 **Lehmann-Waffenschmidt, B. Cornelia:** An Evolutionary Agent-Based Simulation Model for the Industry Lifecycle

11/08 **Mukherjee, Vivekananda / Ramani, Shyama V.:** R&D Cooperation, Asymmetrical Technological Capabilities and Rationale for Technology Parks