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ABSTRACT

To Reveal or not to Reveal: The Case of Research Joint Ventures with Two-Sided Incomplete Information*

Firms' incentives to form Research Joint Ventures (RJVs) are analysed in an incomplete information framework when technological know-how is private information. Firms first decide on cooperation and information revelation and then compete for a patent. Provided that spillovers exist in the case of unilateral revelation of know-how, it can be shown that non-cooperation is always an equilibrium. If competition is in a second-price auction with positive minimum R&D requirements this equilibrium is unique for high spillovers. Cooperation can occur for low spillovers. For certain parameters there exists an equilibrium in which only firms with low know-how cooperate.

JEL Classification: D82, L13, O31
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NON-TECHNICAL SUMMARY

Although there is a broad literature on Research Joint Ventures (RJVs) the aspect of incomplete information has been widely ignored in the industrial organization analysis. This is especially striking since information about firms' know-how and technological competencies (including research costs and strategies) is definitely not public information. Thus, if two firms co-operate it should be natural to assume that there is incomplete information about the other's know-how. And since the know-how of each firm directly determines the possible pay-offs of all parties, firms face a dilemma: while revelation of information is necessary to determine the benefits of cooperation, there is at the same time the risk to be exploited. Very often revelation of information directly includes transferring valuable know-how.

There are a few papers approaching this issue from an optimal contract perspective, most of them are assuming (and have to assume) that information is revealed to an 'intelligent coordinator'. Furthermore, there it is assumed that know-how is substitutable such that only the one party with the most know-how needs to disclose in order to achieve efficiency.

In this paper I present a model in which information is complementary. All parties may benefit from their opponent's information, and disclosure directly includes transferring valuable know-how. I explicitly focus on a situation with no contract and no coordinating third party, to analyse the incentives of two otherwise competing players to form a joint venture and to reveal their know-how.

Thus, the model allows the explicit integration of those features that are idiosyncratic to R&D, i.e. as spillovers, and it also allows the analysis of type-dependent strategies if there is incomplete information on both sides. Both those features seem to be most relevant when analysing research joint ventures: in the complete information framework it has been outlined that the internalization of spillovers is a driving force behind cooperation in research activities, and that the degree of spillovers directly determines possible welfare implications. And, more recently it has been shown empirically that especially heterogeneous firms participate in RJVs. I present a very simple model in which both these aspects can be analysed in the framework of incomplete information.

1. Introduction

Imagine the case of an economist who one morning awakes with a brilliant idea about an important problem he wants to write a paper on. But instead of writing this paper alone the economist prefers to co-author this paper with a mathematician because this would go faster, thus diminish the chance that someone else publishes the same idea earlier and would also be more fun. The economist knows only one mathematician he could ask on this matter but, unfortunately, does not know too much about the mathematician's economic abilities or about his trustworthiness. If the economist tells this person his idea, he not only risks a rejection of the co-authorship but also a publication on this problem by the mathematician alone. What could we suggest the economist? The same problem the economist is confronted with, also frequently is faced by an R&D manager who meets a competitor's representative to negotiate a possible research joint venture. The dilemma is that while information has to be revealed in order to determine possible benefits of cooperation, revelation also bears the risk to be exploited.

Although there is a broad literature on research joint ventures, the problem of incomplete information about the other firm's know-how or technological competencies has been largely neglected in the industrial organization analysis.[1] There are a few papers approaching this issue from an optimal contract perspective: Gandal & Scotchmer [1993] extend the analysis of research joint ventures by assuming that research abilities are private information. Interpreting a joint venture as a "team-problem", they show that optimal rates of R&D investment can be implemented as long as investments are observable. In their model firms can signal their research abilities without revealing know-how such that the above described dilemma does not exist. Bhattacharya, Glazer & Sappington [1990, 1992] focus on optimal mechanisms for the sharing of know-how under the assumption that firms independently compete in the R&D and product market. In both models they restrict their analysis to the case in which firms' knowledge can be ordered in a Blackwell sense, and thus is substitutable, whereas the focus in this paper is on complementary know-how. Here even a firm with low know-how may have an incentive to reveal, while this can never occur in Bhattacharya, Glazer & Sappington [1990, 1992]. This alternative characterization of knowledge seems to be a natural extension to their model. Furthermore, on top of know-how sharing I additionally allow for coordination of research activities as to maximize joint

[1] See for example the fundamental work by D'Aspremont & Jacquemin [1988] which led to about 40 extensions in the following years, or see De Bondt [1996] or Rosenkranz [1996] for surveys on that topic.

profits. D'Aspremont, Bhattacharya & Gérard-Varet [1995] consider a problem of bargaining over the disclosure of interim research knowledge between two parties in an R&D race or contest, for a patentable innovation. While again know-how is assumed to be substitutable, they analyze optimal licensing fee schedules only for one-sided revelation while in this paper the focus is on the bilateral situation. An analogous "one-sided" problem is modeled by Anton & Yao [1994]. In an incomplete contract framework, they analyze the problem faced by a single independent inventor when selling a valuable, but easily imitated, invention for which no property rights exist. The inventor can protect his know-how by negotiating a contingent contract prior to revealing the invention or can reveal the invention and then negotiate with the informed buyer. They find that an inventor with little wealth prefers the latter approach. While in their paper the threat of selling the invention to a competitor is the driving force behind know-how revelation here firms may have an incentive to reveal even without being able to threat. Pérez-Castrillo & Sandonís [1996] analyze the incentives of two asymmetric firms to disclose their know-how in a scenario of uncertainty and asymmetric information and focus on the existence of incentive contracts. In contrast to the model of Pérez-Castrillo & Sandonís, who assume that possible negative effects of know-how revelation stem from future product market competition, in this paper it is assumed that possible negative effects are exhibited by the R&D race itself.

Another branch of literature concentrates on the problem of information sharing and strategic information revelation. A number of papers (e.g., Clarke [1983], Gal-or [1985, 1986], Novshek & Sonnenschein [1982]) have considered whether firms that have private information would have higher profits when information is shared with other firms than when it is kept private. The distinctive assumption in this literature is that firms decide on information sharing before they actually know the realization of their own type, while in the problems presented before, the players are aware of their own know-how when they decide to cooperate.

Okuno-Fujiwara, Postlewaite & Suzumura [1990] model strategic revelation of private information via public disclosure by adding a first stage announcement game to a given game with asymmetric and incomplete information. Agents are allowed to certifiably announce some or all of their private information by announcing a set of types. In contrast, I present a model in which the revelation of information directly includes transferring valuable know-how. Thus, the model allows the explicit integration of those features that are idiosyncratic to R&D, as i.e. spillovers, and it also allows to analyze type-dependent strategies if there is incomplete information on both sides. Both of these features seem to be most relevant when analyzing research joint ventures: In the complete information framework it has been outlined that the internalization of spillovers is a driving force behind cooperation in research activities, and that the degree of spillovers directly determines possible welfare implications.[2] And more recently it has been shown empirically that especially heterogeneous firms participate in research joint ventures.[3] In the following sections I present a very simple model in which both these aspects can be analyzed in the framework of incomplete information.

2. The model

Formally, a non-cooperative two-stage game with (observed actions and) incomplete information is analyzed. Assume there are two players $i = 1, 2$ with types $\mathfrak{v}_i$. Both players believe that the $\mathfrak{v}_i$ are independent and have only two possible values v_l and v_h, (with $v_l < v_h$). Furthermore, they believe that p is the probability that $\mathfrak{v}_i$ equals v_h and that $(1-p)$ is the probability that $\mathfrak{v}_i$ equals v_l. Each player's type $\mathfrak{v}_i$ is private information only to that player. Assume that players' types are given by their *technological know-how.* This know-how may determine their valuations $\mathfrak{v}_i$ for a given patentable innovation in an (deterministic) auction model, or (in a stochastic framework) may represent a probability of invention in

[2] See for example D'Aspremont & Jacquemin [1988] or Katz & Ordover [1990].
[3] See Veugelers & Kesteloot [1995] or Roeller & Tomback [1996].

a contest model or even a Poisson intensity of invention in a patent race model. They play the following two-stage game:

On the *first* stage they both have two possible actions 'cooperate' or 'do not cooperate', denoted by $A_i \in \{C, D\}$ on which they decide simultaneously. If a player chooses action C (cooperate) he reveals his technological know-how and offers a signed joint venture contract. If he chooses D he does not reveal his know-how and does not offer a contract. If both players choose C then they are confronted with a binding contract and form a joint venture. For simplicity it is assumed that players face an "all or nothing" decision, such that, should they decide to cooperate, they reveal their type completely and truthfully.[4]

Once know-how is revealed it definitely is not lost for the one who revealed it, but it may also not be possible to be taken back.[5] Assuming that players' technological know-how is complementary, one might think of two polar cases: If there are no spillovers, the revelation of technological know-how will only reduce uncertainty concerning the other player's type; if there are perfect spillovers, revelation of technological know-how will improve the other player's technological

[4]This is definitely a restrictive assumption for the sake of simplicity and one could think of several different scenarios in which players only reveal as little of their know-how as necessary to "signal" their type.

[5]We abstract from any spillovers due to backward engineering or espionage. Therefore there is no leakage of know-how if players choose not to reveal.

know-how and therefore increase his valuation for the patent or his probability of invention. Let $\alpha \in [0,1]$ denote the degree of spillovers which is common knowledge to both players.[6] Whenever one player j unilaterally reveals his know-how, the other player i's know-how is increased by $\alpha \mathfrak{v}_j$. If players form a joint venture, their technological know-how is always perfectly transferred at no cost. The know-how of the joint venture corresponds to the sum of the individual know-how.

At the beginning of the second stage players can find themselves in four different situations depending on the choice of both their actions at the first stage: Either none of the two players cooperated, only one cooperated or both cooperated and a joint venture is formed.

On the *second* stage the players compete against each other with their know-how for a given patent. In the paper, I present the case in which they participate in a second-price auction for the patent. In the appendix a stochastic contest model is presented for comparison.[7]

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[6] In a patent race with technological spillovers a firm's know-how may have two effects on a rival's probability of success: The more know-how a firm i has, the more likely it is to pre-empt its rival and therefore the success probability of its rivals may be lowered. Second, a rival's probability of success, conditional on not being pre-empted by firm i, rises due to spillovers if firm i unilaterally reveals its know-how. See the contest model in the appendix and also Katz & Ordover [1990].

[7] The second stage can also be modeled as a first price auction or as a patent race in which the $\mathfrak{v}_i$ are representing the Poisson intensities of invention. Since the results remain qualitatively the same, these varieties are not presented here (their presentations are a little more complex) but are available from the author on request.

In an auction, the more superior is a player's technological know-how, the higher is his valuation and the more he is willing to spend on R&D, hence the more likely he wins the patent.[8] At this stage, players' actions are their bids b_i, unless players form a joint venture. Then their bid is b_{JV}, and they win the patent but they have to spend a certain amount of minimum R&D expenditures. The minimum R&D which is required for a patentable innovation is fixed and given by $v_s \in [0, v_l]$ and is common knowledge. The gains in the joint venture are shared according to the initial contributions of know-how.

Note that a strategy of the two-stage game consists of two action plans. At the first stage an action plan of a player i is a mapping from the set of types $\{v_l, v_h\}$ into actions $A_i \in \{C, D\}$. At the second stage his action plan maps the set of types and first stage actions $\{v_l, v_h\} \times \{C, D\} \times \{C, D\}$ into the set of positive real numbers $b_i \in \mathbb{R}^+$. To find perfect Bayesian Nash equilibria, the game is analyzed by backward induction.

[8]Although the timing is not modeled explicitly here it might be helpful to interpret the auction in the following way: A firm committing R&D funds today determines the eventual date of its invention. Since invention is completely deterministic, the firm which commits the greatest expenditures today will obtain the invention first. For simplicity we assume that no real resources are expended until the winner is determined. Although this is a very restrictive assumption it is commonly made in deterministic patent race models, as for example by Dasgupta & Stiglitz [1980]. It is necessary to guarantee for the existence of pure strategy equilibria in this framework. For a discussion see Reinganum [1989].

3. The second stage: A simple second-price auction

In a second-price auction the highest bidder wins the patent and pays the second highest bid, i.e., if he wins $b_i \geq \max_{i \neq j} b_j$. In case of a tie the player wins the patent with probability $\frac{1}{2}$ and pays his bid b_i. Bidder i's payoffs at this stage of the game are given by:

$$\begin{array}{ll} \mathfrak{v}_i - b_j & \text{if } i \text{ wins the patent without } j\text{'s know-how,} \\ \mathfrak{v}_i + \alpha \mathfrak{v}_j - b_j & \text{if } i \text{ wins the patent with } j\text{'s know-how,} \\ \mathfrak{v}_i - \frac{\mathfrak{v}_i}{\mathfrak{v}_i + \mathfrak{v}_j} b_{JV} & \text{if the joint venture wins the patent,} \\ 0 & \text{else,} \end{array}$$

with b_{JV} being the bid of the joint venture, which is shared according to players' contribution of know-how. At the second stage, Bayesian Nash equilibria are characterized by the fact that the optimal bidding strategy for player i, with $i = 1, 2$, is a weakly dominant strategy: Each player bids his valuation (which in this model is given by his technological know-how). Therefore, equilibrium payoffs at this stage do not depend on the updated beliefs.

Let me introduce the following notation: Define player i's payoff given he is of type v_μ and has chosen action A_i, and given player j is of type v_ν and has chosen action A_j (with $\mu, \nu = l, h$ and $i, j = 1, 2$) as: $\Pi_i(A_i, A_j, v_\mu, v_\nu) \equiv \Pi_{\mu\nu}^{A_i A_j}$.

Given that none of the players has revealed any know-how at the first stage (both players chose D) the equilibrium payoffs of players with type v_h and type v_l, respectively, are given by:

$$\begin{aligned}\Pi_{hl}^{DD} &= v_h - v_l \text{ and } \Pi_{lh}^{DD} = 0, \text{ or} \\ \Pi_{hh}^{DD} &= \Pi_{ll}^{DD} = 0.\end{aligned}$$

If they form a joint venture (C_i, C_j), their valuation is given by $\mathfrak{v}_i + \mathfrak{v}_j$ while they only bid the minimum R&D v_s.[9] As stated before, suppose that they share the bid according to their contribution of know-how. The payoff of player 1 with type v_μ cooperating with a player 2 of type v_ν, with $\mu, \nu = l, h$, is given by:

$$\Pi_{\mu\nu}^{CC} = v_\mu - \frac{v_\mu}{v_\mu + v_\nu} v_s \text{ with } \mu, \nu = l, h.$$

In case that only one of the two players offers a signed contract and reveals all his technological know-how, his opponent can win the auction given that he can

[9] Actually I assume that they form a bidder ring. See Graham & Marshall [1987].

overbid. So in case player 1 is of type v_h and *receives* know-how without revealing himself, his payoff is:

$$\begin{aligned} \Pi^{DC}_{hl} &= v_h - (1-\alpha)v_l, \text{ or} \\ \Pi^{DC}_{hh} &= \alpha v_h, \end{aligned}$$

depending on the type of player 2. Note that even a player of type v_l can overbid a player with type v_h if $\alpha > \alpha^* \equiv 1 - \frac{v_l}{v_h}$. The payoff of a player of type v_l given the other has unilaterally revealed his know-how is:

$$\Pi^{DC}_{lh} = \begin{cases} v_l - (1-\alpha)v_h & \text{if } \alpha \geq \alpha^*, \\ 0 & \text{if } \alpha < \alpha^*, \end{cases} \quad \text{or}$$

$$\Pi^{DC}_{ll} = \alpha v_l.$$

While the payoff of player 1 given that he has unilaterally *revealed* his know-how is either:

$$\Pi^{CD}_{lh} = \Pi^{CD}_{hh} = \Pi^{CD}_{ll} = 0, \text{ or}$$

$$\Pi_{hl}^{CD} = \begin{cases} 0 & \text{if} \quad \alpha \geq \alpha^*, \\ v_h(1-\alpha) - v_l & \text{if} \quad \alpha < \alpha^*. \end{cases}$$

Let us first establish the following relations between players' profits:

$$\begin{aligned} \Pi_{hl}^{CC} &> \Pi_{hl}^{DC} \text{ for } \alpha < \alpha_1 \equiv 1 - \frac{v_h v_s}{v_l(v_h + v_l)}, \\ \Pi_{ll}^{CC} &> \Pi_{ll}^{DC} \text{ for } \alpha < \alpha_2 \equiv 1 - \frac{v_s}{2v_l}, \\ \Pi_{hh}^{CC} &> \Pi_{hh}^{DC} \text{ for } \alpha < \alpha_3 \equiv 1 - \frac{v_s}{2v_h}, \\ \Pi_{lh}^{CC} &> \Pi_{lh}^{DC} \text{ for } \alpha < \alpha_4 \equiv 1 - \frac{v_l \; v_s}{v_h(v_h + v_l)}. \end{aligned} \tag{3.1}$$

A comparison yields $\alpha_1 \leq \alpha_2 \leq \alpha_3 \leq \alpha_4 \leq 1$ for $v_s \geq 0$. Note that in order for a player i to benefit from unilateral cheating, spillovers have to be higher, the higher is the rival's know-how in relative and absolute terms.

Now equilibria of the two-stage game can be characterized. But before I outline the players' optimal strategies, I will briefly describe possible equilibria in the first stage game under the assumption of general reduced form profit functions which are generated in the second-stage equilibria.

4. The first stage: The cooperation decision

In the previous section it was shown that players' second stage equilibrium profits are independent from updated beliefs about their opponents type. This fact simplifies the subsequent analysis. We can restrict ourselves to look for Bayesian Nash equilibria in a game of incomplete information with a finite number of types $\mathfrak{v}_i$ for each player i, prior distribution p, and pure-strategy space S_i.[10]

Denote the probability that player i of a given type μ chooses action $A_i = C$ as z_i^μ, with $\mu = l, h$. A player 1's expected payoff $E_\mu(p, z_1, z_2(\mathfrak{v}_2), (\mathfrak{v}_1, \mathfrak{v}_2))$ can then be written as:

$$
\begin{aligned}
E_\mu \;=\;& p[z_1^\mu z_2^h \Pi_{\mu h}^{CC} + z_1^\mu(1 - z_2^h)\Pi_{\mu h}^{CD} \\
& +(1 - z_1^\mu)z_2^h \Pi_{\mu h}^{DC} + (1 - z_1^\mu)(1 - z_2^h)\Pi_{\mu h}^{DD}] + \\
& (1 - p)[z_1^\mu z_2^l \Pi_{\mu l}^{CC} + z_1^\mu(1 - z_2^l)\Pi_{\mu l}^{CD} \\
& +(1 - z_1^\mu)z_2^l \Pi_{\mu l}^{DC} + (1 - z_1^\mu)(1 - z_2^l)\Pi_{\mu l}^{DD}].
\end{aligned}
$$

Differentiation of the expected payoff with respect to z_1^μ yields the following co-

[10] Equilibria in this game will naturally satisfy all requirements of perfect Bayesian equilibria.

efficients:

$$E'_\mu = p[z_2^h(\Pi_{\mu h}^{CC} - \Pi_{\mu h}^{CD} - \Pi_{\mu h}^{DC} + \Pi_{\mu h}^{DD}) + \Pi_{\mu h}^{CD} - \Pi_{\mu h}^{DD}] + (1-p)[z_2^l(\Pi_{\mu l}^{CC} - \Pi_{\mu l}^{CD} - \Pi_{\mu l}^{DC} + \Pi_{\mu l}^{DD}) + \Pi_{\mu l}^{CD} - \Pi_{\mu l}^{DD}].$$

We are only interested in *symmetric* equilibria in *pure* strategies, that is whenever $z_2^{l*} = 0$, we want player 1 of type l to also choose $z_1^{l*} = 0$.

Define the first stage action of a player i of type v_μ as A_i^μ. The action pairs (D_i^h, D_j^l) for $i, j \in \{1, 2\}$ and $i \neq j$, are equilibria if, given $z_2^h = 0$ and $z_2^l = 0$, a player 1 of type v_h will choose $z_1^h = 0$ and a player 1 of type v_l will also choose $z_1^l = 0$, i.e. if the following inequality holds for both types $\mu = l, h$:

$$p(\Pi_{\mu h}^{CD} - \Pi_{\mu h}^{DD}) + (1-p)(\Pi_{\mu l}^{CD} - \Pi_{\mu l}^{DD}) < 0. \tag{4.1}$$

The action pairs (C_i^h, C_j^l) for $i, j = 1, 2$, are equilibria if, given $z_2^h = 1$ and $z_2^l = 1$, a player 1 of type v_h will choose $z_1^h = 1$ and a player 1 of type v_l will also choose $z_1^l = 1$, i.e. if the following inequality holds for both types $\mu = l, h$:

$$p(\Pi_{\mu h}^{CC} - \Pi_{\mu h}^{DC}) + (1-p)(\Pi_{\mu l}^{CC} - \Pi_{\mu l}^{DC}) > 0 \tag{4.2}$$

Only players of type v_l cooperate (the action pairs (D_i^h, C_j^l) for $i, j \in \{1,2\}$ and $i \neq j$ are equilibria) if, given $z_2^h = 0$ and $z_2^l = 1$ a player 1 of type v_h will choose $z_1^h = 0$ and a player 1 of type v_l will choose $z_1^l = 1$, i.e. if :

$$p(\Pi_{hh}^{CD} - \Pi_{hh}^{DD}) + (1-p)(\Pi_{hl}^{CC} - \Pi_{hl}^{DC}) < 0, \text{ and} \tag{4.3}$$

$$p(\Pi_{lh}^{CD} - \Pi_{lh}^{DD}) + (1-p)(\Pi_{ll}^{CC} - \Pi_{ll}^{DC}) > 0. \tag{4.4}$$

On the other hand, only players of type v_h cooperate (the action pairs (C_i^h, D_j^l) for $i, j \in \{1,2\}$ and $i \neq j$ are equilibria) if, given $z_2^h = 1$ and $z_2^l = 0$ a player 1 of type v_h will choose $z_1^h = 1$ and a player 1 of type l will choose $z_1^l = 0$. This is the case if :

$$p(\Pi_{hh}^{CC} - \Pi_{hh}^{DC}) + (1-p)(\Pi_{hl}^{CD} - \Pi_{hl}^{DD}) > 0, \text{ and} \tag{4.5}$$

$$p(\Pi_{lh}^{CC} - \Pi_{lh}^{DC}) + (1-p)(\Pi_{ll}^{CD} - \Pi_{ll}^{DD}) < 0. \tag{4.6}$$

It is easily seen that whenever $\Pi_{\mu\nu}^{CC} > \Pi_{\mu\nu}^{DC}$ for all $\mu, \nu = l, h$ then (4.2) is satisfied and (C_i^μ, C_j^ν) is always an equilibrium. If additionally $\Pi_{\mu\nu}^{CD} > \Pi_{\mu\nu}^{DD}$ then (C_i^μ, C_j^ν) with $i, j \in \{1,2\}$ and $i \neq j$ is also the unique equilibrium and the game can be characterized as a Prisoner's Dilemma (PD) with an efficient outcome.

Analogously, if $\Pi_{\mu\nu}^{CD} < \Pi_{\mu\nu}^{DD}$ then (4.1) is satisfied and (D_i^μ, D_j^ν) is always an equilibrium and if additionally $\Pi_{\mu\nu}^{CC} < \Pi_{\mu\nu}^{DC}$ then no-cooperation is the unique equilibrium. In this case the game corresponds to the classical PD situation.

On the other hand, if $\Pi_{\mu\nu}^{CC} > \Pi_{\mu\nu}^{DC}$ holds and at the same time also $\Pi_{\mu\nu}^{CD} < \Pi_{\mu\nu}^{DD}$ then both these equilibria exist, which is known as a 'coordination game'. Due to incomplete information in this framework there is also the potential for equilibria with (C_i^l, D_j^h) or (C_i^h, D_j^l) depending on the parameter values of p and possibly also on other parameter values of the second stage subgame. The same kind of equilibria occur as unique equilibria if $\Pi_{\mu\nu}^{CD} < \Pi_{\mu\nu}^{DD}$ as well as $\Pi_{\mu\nu}^{CC} < \Pi_{\mu\nu}^{DC}$ only holds for one type μ of player i but not for the other. These are obviously the more interesting cases.

5. Bayesian equilibria of the two-stage auction game

Having established payoffs and equilibrium conditions in both subgames, we can now state some results. First off all it turns out that two factors are critical: The level of spillovers (or the degree of transferability of know-how), as well as the level of minimum R&D.

Remark 1. *If $v_s = 0$ the game is a 'coordination game'. In one equilibrium players of both types cooperate $\left(C_i^{\mu}, C_j^{\mu}\right)$ and in the other equilibrium players of* *both types do not cooperate* $\left(D_i^{\mu}, D_j^{\mu}\right)$.

Obviously, if the are no minimum R&D expenditures, we find $\Pi_{\mu\nu}^{CC} > \Pi_{\mu\nu}^{DC}$for both types. At the same time, $\Pi_{\mu\nu}^{CD} < \Pi_{\mu\nu}^{DD}$always holds. This changes if we consider positive minimum R&D expenditures:

Proposition 5.1. *Assume $v_s > 0$. No-cooperation $\left(D_i^{\mu}, D_j^{\mu}\right)$ is always an equilibrium. If spillovers are sufficiently large, $\alpha > \alpha_3$, then no-cooperation $\left(D_i^{\mu}, D_j^{\mu}\right)$ is a unique equilibrium for all p, and $v_s > 0$.*

Proof: First note that $\Pi_{\mu\nu}^{CD} \leq \Pi_{\mu\nu}^{DD}$ always holds. Additionally, if $v_s > 0$, then $\alpha_3 < \alpha_4 < 1$. If $\alpha > \alpha_4$ then $\Pi_{\mu\nu}^{CC} < \Pi_{\mu\nu}^{DC}$ holds and D (no cooperation) is a dominant strategy for both types. If $\alpha > \alpha_3$ then $\Pi_{lh}^{CC} > \Pi_{lh}^{DC}$ holds, but this is not enough to satisfy (4.2). Checking conditions (4.3) to (4.6) it is easy to see that there is no other candidate for an equilibrium. □

This first result is straightforward. If spillovers are large, the gains from cheating outweigh the gains from cooperating for all players and the game resembles a Prisoner's Dilemma situation. Hence, no cooperation must be a dominant strategy. It follows that it is very unlikely that firms cooperate if their know-how is easily transferable whenever it is revealed. It might be interesting to note that spillovers need not be perfect for this situation to occur. The higher the minimum

R&D required for an innovation, the smaller can be the spillovers such that firms are in this PD situation.

Proposition 5.2. *Assume $v_s > 0$. Cooperation $\left(C_i^{\mu}, C_j^{\mu}\right)$, with $i,j = 1,2$, is an equilibrium if*

(i) for all p, v_s spillovers are sufficiently small, $\alpha \leq \alpha_1$, or

(ii) if $\alpha < \alpha_3$ and $p > p^*$,with

$$p^* \equiv \frac{2(1-\alpha)(v_h v_l + v_l^2) - 2v_h v_s}{2(1-\alpha)(v_l^2 - v_h^2) - v_s(v_h - v_l)}.$$

Proof: First note that $\alpha \leq \alpha_1$ implies $\Pi_{\mu\nu}^{CC} \geq \Pi_{\mu\nu}^{DC}$ for all types and, hence, cooperation $\left(C_i^{\mu}, C_j^{\mu}\right)$ is an equilibrium. If $\alpha_1 < \alpha < \alpha_3$, we find $\Pi_{ih}^{CC} > \Pi_{ih}^{DC}$ and $\Pi_{hl}^{CC} < \Pi_{hl}^{DC}$ and $0 < p^* < 1$. For $p > p^*$ inequality (4.2) is satisfied for players of type v_h. Obviously (4.2) is more restrictive for players of type v_h than for players of type v_l and therefore $p > p^*$ is enough to guarantee (4.2) to be satisfied for players of both types. □

If spillovers are sufficiently small such that unilateral cheating does not lead to a significant advantage, cooperation is an equilibrium. This is definitely always true if there is no minimum R&D to be paid in case of a joint venture. Even if spillovers are large enough to give the low know-how type an incentive to cheat on the high know-how type, this incentive may be outweighed by the low probability of meeting a high know-how type.

As was already pointed out, the relative magnitude of minimum R&D required for an innovation does play an important role. The higher the minimum R&D the smaller is the relative benefit of cooperation because the joint venture has to pay those minimum R&D costs with certainty.

Proposition 5.3. *Assume $v_s > 0$. For spillovers in the interval $\alpha \in [\alpha_1, \alpha_2]$ and all p there exists an equilibrium in which only players with a low valuation cooperate, (C_i^l, D_j^h) with $i, j = 1, 2$.*

Proof: Note that with $v_s > 0$ we find $\alpha_1 < \alpha_2 < 1$. If $\alpha \in [\alpha_1, \alpha_2]$, due to (3.1) we find $\Pi_{hl}^{CC} < \Pi_{hl}^{DC}$ and $\Pi_{ll}^{CC} > \Pi_{ll}^{DC}$ as well as $\Pi_{lh}^{CD} = \Pi_{lh}^{DD} = \Pi_{hh}^{CD} = \Pi_{hh}^{DD} = 0$. It follows that (4.3) and (4.4) are satisfied. □

If minimum R&D is sufficiently high, there is an intermediate interval of spillovers for which players with low know-how do not loose anything by unilaterally revealing their know-how: If they are confronted with a high know-how type they do not make any profits anyhow, but being confronted with a player of their own type they are better off cooperating. On the other hand, for players with high know-how, spillovers are large enough to benefit from cheating against a low know-how type since minimum R&D is sufficiently high. Hence, there exists an equilibrium in which only players with low know-how cooperate. Although both cut-off levels α_1 and α_2 are decreasing the higher are minimum R&D requirements, the interval $\Delta_\alpha = \alpha_2 - \alpha_1$ is increasing. Furthermore, the higher is the dispersion of know-how between the two players, the larger is Δ_α.

Proposition 5.4. *There never exists an equilibrium in which only players of type v_h cooperate, $\left(D_i^l, C_j^h\right)$ with $i, j = 1, 2$.*

Proof: Note that inequality (4.5) is not even satisfied for $\alpha \leq \alpha_3$ while inequality (4.6) is satisfied for $\alpha > \alpha_4$. Since $\alpha_4 > \alpha_3$ for all $v_s > 0$, inequalities (4.5) and (4.6) can never be satisfied simultaneously. □

Obviously, if spillovers are high enough to give the players with little know-how an incentive to cheat, the players with high know-how will also have an incentive not to cooperate. If there is no minimum R&D required, cooperation is a best response for the low know-how types. But given this strategy, also the high know-how types have no incentive to cheat. Therefore, there is never an equilibrium in which only the players with high know-how cooperate.

6. Conclusion

Although there is a broad literature on research joint ventures the aspect of incomplete information has been widely ignored in the analysis. This is especially striking since information about firms' know-how and technological competencies (including research costs and strategies) is definitely not public information. Thus, if two firms cooperate it should be natural to assume that there is incomplete information about the other's know-how. And since the know-how of each firm directly determines the possible payoffs of all parties, firms face a dilemma: While revelation of information is necessary to determine the benefits of cooperation, there is at the same time the risk to be exploited.

Although the model presented in this paper is oversimplified with respect to the underlying assumptions concerning the process of information revelation as well as the assumptions concerning the patent race, it still generates some clear-cut results concerning the impact of incomplete information on the analysis of research joint ventures.

Turning back to the initially described problems one can suggest the following interpretations of the main propositions. The first results clarify the relevance of spillovers on firms' incentives to cooperate in an incomplete information framework. In case spillovers are rather low, firms (or scientists) have a strong incentive to cooperate, no matter how much know-how they have. The risk of being exploited is small compared to possible gains from unilateral know-how revelation. In contrast, if spillovers are large or technological competencies are easily transferable, firms are in the classical Prisoner's Dilemma situation. They do not cooperate since the gains from "going alone" are large and they end up in an inefficient equilibrium. These two results relate to those of Pérez-Castrillo & Sandonís [1996] as well as to those of Okuno-Fujiwara, Postlewaite & Suzumura [1990]. In comparison to Pérez-Castrillo & Sandonís [1996] our results demonstrate that competition on the R&D market is strategically as important as competition on future product markets for firms' decisions to disclose know-how. In relation to Okuno-Fujiwara, Postlewaite & Suzumura [1990] we can observe that multiple equilibria are possible and that complete revelation of information may occur as well as no revelation. The results are not directly comparable to those of earlier research on the welfare implications of RJVs. There it was found that the impact on welfare is positive only if spillovers are sufficiently large.[11] In the model presented here it is assumed that spillovers are only present if one firm reveals its know-how with the intention to cooperate. By assuming that there are no

[11] See e.g. D'Aspremont & Jacquemin [1988] or Kamien, Müller & Zang [1992].

spillovers at all if none of the firms cooperates, I abstract from backward engineering or espionage as a reason for spillovers. While the payoff of the firm with low know-how is definitely increasing when know-how additionally spills over as a consequence of backward engineering, this is not necessarily true for the high know-how type. Therefore, no-cooperation becomes even more likely at least for the low type. This suggests that firms prefer to cooperate in situations with low spillovers - which means that research joint ventures in general are likely not to be welfare enhancing.

The second result specifies the existence of type-dependent cooperation strategies in an incomplete information framework and thus relates to the question of cooperation between heterogeneous firms. The higher is minimum R&D for a patentable innovation the higher is the incentive to cooperate for firms with low know-how. Given intermediate spillovers (or intermediate probabilities of a type with high know-how in the contest model), there exists an equilibrium in which the low know-how types cooperate, provided that the high know-how types unilaterally cheat. The higher is the dispersion of know-how between the two types (the more superior is the existing technology of one firm), the larger is the interval of spillovers (or probabilities) for this equilibrium to exist. Looking at a population of firms under these circumstances one should expect to observe more low know-how firms to cooperate, while only few of the high know-how firms cooperate.

In a next step it is planed to generalize the model in terms of, e.g., allowing a continuum of types. Furthermore, an incorporation of the dynamic aspect of the above described problems would be more realistic. The 'all-or-nothing' assumption of revealing information can then be modified. It could be assumed that partners meet several times and reveal their information bit by bit. Furthermore, the scenario might be a more sequential one, as well as a situation of a repeated game where especially reputation effects would matter.

7. Appendix

A one-shot contest at the second stage:

Let $\mathfrak{v}_i \in \{v_l, v_h\}$ with $i = 1, 2$ be statistically independent probabilities of invention for the two players conditional on their know-how levels. For a discrete invention or contest model where the value V is lost in case of tied inventions because of Bertrand competition in the product market, we have the following payoffs at the second stage (with $\mu, \nu = l, h$):

$$\begin{aligned}
\Pi^{DD}_{\mu\nu} &= v_\mu (1 - v_\nu) V \\
\Pi^{CC}_{\mu\nu} &= (1 - (1 - v_\mu)(1 - v_\nu)) \frac{v_\mu}{v_\mu + v_\nu} V \\
\Pi^{DC}_{\mu\nu} &= v_\mu (1 - v_\nu) V \\
\Pi^{CD}_{\mu\nu} &\doteq (1 - \alpha) v_\mu (1 - v_\nu) V
\end{aligned}$$

In case of unilateral know-how disclosure the receiving player does not directly benefit from the other player's know-how while the revealing player earns a payoff of $(1-\alpha)v_\mu(1-v_\nu)V$, which is 0 in case of complete spillovers, $\alpha = 1$. This is due to the fact that if a player's know-how leads to a success it does so independently of who owns this know-how. Another consequence is that in case of know-how disclosure by both players simultaneously, the joint venture will only employ once each know-how, and may be successful with either one. As before, in this situation they share the value V according to their initial contributions of know-how.

We can establish the following equilibria at the first stage of the game:

(i) DD is always an equilibrium, since $\Pi^{DD}_{\mu\nu} > \Pi^{CD}_{\mu\nu}$, for all $\mu, \nu = l, h$.

(ii) CC is always an equilibrium since $\Pi_{\mu\nu}^{CC} > \Pi_{\mu\nu}^{DC}$, for all $\mu, \nu = l, h$:

$$\left((v_\mu + v_\nu - v_\mu v_\nu) \frac{v_\mu}{v_\mu + v_\nu} V \right) - (v_\mu (1 - v_\nu) V) = V v_\mu \frac{v_\nu^2}{v_\mu + v_\nu} > 0$$

(iii) C^h, D^l is never an equilibrium. Inequality (4.5) is satisfied for:

$$\begin{aligned} 0 &> p\left((v_h + v_h - v_h v_h) \frac{v_h}{v_h + v_h} V - v_h (1 - v_h) V \right) \\ &\quad + (1-p) \left((1-\alpha) v_h (1 - v_l) V - v_h (1 - v_l) V \right) \\ &\Leftrightarrow \frac{v_h \alpha (1 - v_l)}{\frac{1}{2} v_h^2 + v_h \alpha (1 - v_l)} < p \end{aligned}$$

while (4.6) is satisfied for:

$$\begin{aligned} 0 &< p\left((v_l + v_h - v_l v_h) \frac{v_l}{v_l + v_h} V - v_l (1 - v_h) V \right) \\ &\quad + (1-p) \left(0 - v_l (1 - v_l) V \right) \\ &\Leftrightarrow \frac{(v_l + v_h) \alpha (v_l - 1)}{-v_h^2 + (v_l + v_h) \alpha (v_l - 1)} > p. \end{aligned}$$

There is no interval for p for which both inequalities hold at the same time:

$$\frac{(v_l + v_h) \alpha (v_l - 1)}{-v_h^2 + (v_l + v_h) \alpha (v_l - 1)} - \frac{v_h \alpha (1 - v_l)}{\frac{1}{2} v_h^2 + v_h \alpha (1 - v_l)} =$$

$$\frac{v_h\alpha\,(v_l-1)\,(v_h-v_l)}{(-\alpha(v_l+v_h-v_lv_h)-v_h^2+\alpha v_l^2)\,(-v_h-\alpha(2+2v_l))}<0$$

(iv) C^l, D^h an equilibrium if $p \in [\hat{p}, \check{p}]$. Inequality (4.3) is satisfied for:

$$\begin{aligned} 0 &> p\left((1-\alpha)v_h(1-v_h)V - v_h\,(1-v_h)\,V\right) + \\ &\quad (1-p)\left(\left(v_h+v_l-v_hv_l\right)\frac{v_h}{v_h+v_l}V - v_h\,(1-v_l)\,V\right) \\ \Leftrightarrow &\quad p > \hat{p} \equiv -\frac{v_l}{-2\alpha+2\alpha v_h-v_l}, \end{aligned}$$

while inequality (4.4) is satisfied for:

$$\begin{aligned} 0 &< p\left((1-\alpha)v_l(1-v_h)V - v_l\,(1-v_h)\,V\right) + \\ &\quad (1-p)\left(\left(v_l+v_l-v_lv_l\right)\frac{v_l}{v_l+v_l}V - v_l\,(1-v_l)\,V\right) \\ \Leftrightarrow &\quad p < \check{p} \equiv -\frac{v_l^2}{-\alpha v_l-\alpha v_h+\alpha v_lv_h+\alpha v_h^2-v_l^2}. \end{aligned}$$

The interval $[\hat{p}, \check{p}]$ exists since:

$$\check{p}-\hat{p} = -\frac{v_l}{2\alpha(v_h-1)-v_l} - \left(-\frac{v_l^2}{-\alpha(v_l+v_h-v_lv_h-v_h^2)-v_l^2}\right) =$$

$$\frac{-\alpha v_l\,(v_h-1)\,(v_h-v_l)}{(2\alpha(v_h-1)-v_l)\,(-\alpha(v_l+v_h-v_lv_h-v_h^2)-v_l^2)} > 0 \text{ for } v_h \geq v, \text{ and } \alpha > 0.$$

Obviously the results do not differ drastically from those of the second-price auction. The degree of spillovers is less important whereas the probability of a certain type becomes a critical factor. The reason is that in the contest spillovers only influence the payoff of the unilaterally revealing player while in the auction they influence the payoff of the unilaterally cheating player. Hence, they are less important for the decision to cooperate in a stochastic contest.

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