RIETI Discussion Paper Series 07-E-019

Information Sharing in Joint Research and Development

CHUMA Hiroyuki
RIETI

FUJIMURA Shuzo
Tokyo Institute of Technology

KAWAGOE Toshiji
Future University - Hakodate

MATSUBAE Taisuke
Waseda University

OKUNO (FUJIWARA) Masahiro
the University of Tokyo

TAKIZAWA Hirokazu
RIETI

WATANABE Yasunori
the University of Tokyo

YOKOYAMA Izumi
Hitotsubashi University

RIETI
Research Institute of Economy, Trade & Industry, IAA

The Research Institute of Economy, Trade and Industry
http://www.rieti.go.jp/en/

RIETI Discussion Paper Series 07-E -019

Information Sharing in Joint Research and Development*

CHUMA Hiroyuki†

FUJIMURA Shuzo‡

KAWAGOE Toshiji §

MATSUBAE Taisuke¶

OKUNO-FUJIWARA Masahiro‖

TAKIZAWA Hirokazu**

WATANABE Yasunori††

YOKOYAMA Izumi‡‡

29 March 2007

Abstract

In today's science-driven industries, such as the semiconductor industry, firms are increasingly engaged in across-firm research and development projects in the form of a research consortium or a strategic alliance. Those collaboration processes, however, have complex aspects due to the competing relationship of the firms in product markets and will not be successful unless the participating firms have enough incentives to reveal their private information and to exert sufficient efforts. The paper attempts to explore the conditions under which firms have enough incentives to reveal their information and/or to expend collaborative efforts. Three existing economic models are examined for this purpose. It is argued that those incentives depend upon the nature of competition in the product markets, information structure, and the way that each firm's private information affects this competition. The models examined in the paper suggest that some mechanism is necessary to evaluate private technical information of each firm and to convey it to the other firms without distortion. This conclusion coincides with the observed fact that a neutral third-party plays an indispensable role in a successful research consortium.

*This research was undertaken as part of the RIETI research project "Theoretical and Experimental Research on Mechanisms of Communication, Coordination and Collaboration." The authors thank Takayuki Sumita (METI), Kazuhiro Ueda (University of Tokyo), Nobuo Fudanuki (STARC), Koichi Suga (Waseda University), Noriyuki Yanagawa (University of Tokyo), Hideshi Itoh (Hitotsubashi University), Akio Kondo (NISTEP), Akira Goto (University of Tokyo), William Spencer (the former president of SEMATEC) and other seminar participants at RIETI and NISTEP. Any remaining errors are ours. The views expressed in the paper are the opinions of the authors' and do not necesarily reflect the views of organization to which they belong.

†Hitotsubashi University

‡Tokyo Institute of Technology

§Future University — Hakodate

¶Waseda University

‖University of Tokyo

**RIETI

††University of Tokyo

‡‡Hitotsubashi University

1 Introduction

Today's science-driven industries, as represented by the semiconductor inductry, seem to be facing unprecedented chages in R&D environments: enormous amounts of necessary R&D investment; wider scope, growing complexity, and speed-up of the R&D activities; and an increasing degree of marketing uncertainty. Those changes are making it increasingly difficult for each firm in the industries to conduct its whole R&D process in house, giving rise to increased instances of collaborative R&D activities across firms in the form of strategic alliances and/or research consortia (Lamoreaux et al. 2003; Sable and Zeitlin 2004). While proven to be quite effective, however, the collaborative relationship in the R&D activities has complex aspects, sometimes plagued by conflicting interests of participating firms that typically compete in the product markets. We believe that information sharing is the key to successful collaboration and that exploring the incentives for the participants to do so is vital in understanding the process of collaborative R&D.

This paper explores the incentives of collaborating firms to share/reveal their private information and to exert efforts in the joint process of R&D process, by examining existing literature in economics. The major forms of the real-world collaborative R&D process are known to be strategic alliance and research consortium. Although understanding the difference of the two forms should be an interesting topic in itself, we will not delve into the issue here. Rather we choose to examine the incentives of collaborating firms in abstract models. However, we will try to relate the results obtained in the models to the complex real-world situation wherever possible. In fact, our conclusion is related to the observed practice in real-world research consortia.

Examining the logic and/or conclusion of three existing economic models, it is argued that the firms' incentives to reveal information and to exert effort depend much upon the nature of the competition in the product markets, information structure, and the way that each firm's private information affects this competition. It is also suggested that some mechanism be necessary to evaluate private technical information of each firm and to convey it to other firms without distortion. This conclusion coincides with the observed fact that a neutral third-party plays an indispensable role in a successful research consortium (Chuma 2003).

The organization of the paper is as follow. Section 2 deals with the incentive problems that arise when firms are to share private information that cannot be controlled by their actions. In Section 2.1, we examine the canonical model of the oligopoly competition with asymmetric information, where firms compete in an oligopoly market with private information. The *ex ante* incentives of those firms to share/reveal information is examined. In this model, it is assumed that firms can commit to their revelation/nonrevelation strategy even after receiving private signals. The model may be interpreted as a situation where firms are engaged in long-term competing relationships with one another in their product markets and consider participating in a trade association where they are required to reveal their private information honestly. In contrast to this model, the model in Section 2.2 does not assume that firms can make a commitment to reveal undistorted information upon receiving private signals. Firms decide whether or not to reveal their information after receiving it and they can distort it if they wish to do so. This model seems to be closer to the real situation firms face in a strategic alliance or a research consortium. The model in Section 2.1, however, provides a benchmark for evaluating the implication for the welfare of firms in different informational environments. Section 3 deals with the impact of information sharing at an *interim* stage on firms' incentive to exert efforts in the ongoing process of collaborative R&D. Finally Section 4 concludes.

2 Incentives to Share Information Regarding Exogenous Parameters

2.1 Information Sharing in an Oligopoly Market with Asymmetric Information

In launching a new joint project in a strategic alliance or a research consortium, firms are usually supposed to be willing to cooperate with one another. Sometimes, however, they find difficulties in initiating a new joint project, because it requires all participating firms to reveal their respective information relevant to the project and firms tend to regard their private information as a source of their competitiveness. Under what conditions do firms have incentives to reveal their information required for the joint project? How does the nature of competitive relations in their product markets affect the incentive to share/reveal information in the joint R&D process?

A well-known economic model relevant to this question is the model of information sharing in an oligopoly market wih asymmetric information. The question whether firms competing in a oligopoly market with asymmetric information have any incentives to share their private information had long plagued industrial organization theorists since the mid 1980's. Various models with different conclusions appeared and it seemed that getting a decisive answer to the question was difficult. However, Raith(1996) finally succeeded in giving a lucid answer[10]. This subsection reviews his model.

Suppose that firms, indexed by $i = 1, \cdots, n$, play a game as follows. At the first stage, each firm decides whether or not to reveal its private information to be later obtained. After the decision, each firm receives a private signal regarding its payoff-relevant parameter and reveals the obtained signal if it decides to do so at the first stage. All the revealed information is pooled and made public. At the second stage of the game, firms compete in the oligopoly market, using all the available information. Note that, in this model, it is assumed that firms can commit to the revelation decision made at the first stage after receiving any private signal.

The following symmetric quadratic payoff function for firm i is considered:

$$\pi_i = \alpha_i(\tau_i) + (\beta_n + \gamma_n \tau_i - \epsilon s_i) \sum_{j \neq i} s_j + (\beta_s + \gamma_s \tau_i - \delta s_i) s_i, \tag{1}$$

where τ_i is a random parameter with $\tau_i \sim N(0, t_s)$, $Cov(\tau_i, \tau_j) = t_n (i \neq j)$. $\alpha_i(\cdot)$ is a function, s_i is the strategic choice made by firm i at the second stage competition. $\beta_n, \gamma_n, \epsilon, \beta_s, \gamma_s, \delta$ are parameters. To ensure that the payoff function is derivable from a linear demand system, it is assumed that $\epsilon \in (-\delta/(n-1), \delta]$. To make the payoff function concave, it is also assumed that $\delta > 0$.

Imposing different restrictions on the parameters, the above payoff function can express various payoffs that arise in Cournot or Bertrand competition in markets with demand or cost uncertainty (in the Cournot case, quadratic production costs can also be accomodated). Uncertainty takes the form of a random demand intercept or random marginal cost in this function. With zero mean, τ_i is a deviation from the mean demand intercept or mean marginal cost. In the case of demand uncertainty, we have $\gamma_s = 1$ in both Cournot and Bertrand models. In the case of cost uncertainty in Cournot competition, $\gamma_s = -1$. In all these three cases, $\gamma_n = 0$, while in the Bertrand competition with cost uncertainty we have $\gamma_n \neq 0$. Whether or not $\gamma_n = 0$ matters a lot in the conclusion below, although this looks just a technical subtlety.

[10]For a survey of the related literature, see Vives (1999).

For example, to obtain a Cournot payoff function with demand uncertainty, let $\alpha = 0, \beta_n = 0, \gamma_n = 0, \gamma_s = 1$. With $s_i = q_i$, the payoff function assumes the following form:

$$\pi_i = (\beta_s + \tau_i - \delta q_i - \epsilon \sum_{j \neq i} q_j) q_i.$$

This is the profit of firm i in the Cournot competition when the demand function for firm i is $p_i = \beta_s + \tau_i - q_i - \epsilon \sum_{j \neq i} q_j$ and the cost function is $c_i = (\delta - 1) q_i$. For other specifications of parameters in other cases, see Table 1.

	Cournot Model	Bertrand Model
Demand Uncertainty	$\alpha_i = 0, \beta_n = 0, \gamma_n = 0, \gamma_s = 1$	$\alpha_i = 0, \beta_n = 0, \gamma_n = 0, \gamma_s = 1$
Cost Uncertainty	$\alpha_i = 0, \beta_n = 0, \gamma_n = 0, \gamma_s = -1$	$\alpha_i(\tau_i) = -\beta_s \tau_i, \beta_n = 0, \gamma_n = \epsilon, \gamma_s = \delta$

Table 1: Parametric Restrictions to Express Various Models of Oligopoly Competition with Uncertainty

Between the first and the second stages, firm i observes a private signal $y_i := \tau_i + \eta_i$, where η_i is an observation error. We let $\tau = (\tau_1, \cdots, \tau_n)$ and $\eta = (\eta_1, \cdots, \eta_n)$. Regarding the error, we assume $\eta_i \sim N(0, u_{ii})$ for all i, and $Cov(\eta_i, \eta_j) = u_n \in [0, \min_i\{u_{ii}\}]$ for all $i \neq j$. We also assume that for all i and j, τ_i and η_j are independent. As a technical assumption, the correlation of the observation errors is assumed to be less than the correlation of the payoff-relevant parameters: $t_n u_{ii} \geq t_s u_n$ for all i.

This formulation encompasses the three distinctive information structure as follows:

- Common Value (CV): $\rho(\tau_i, \tau_j) = 1$ for all $i \neq j$: All the τ_i's are equal with probability one.
- Perfect Signals (PS): $\eta_i = 0$ for all i and $0 < \rho(\tau_i, \tau_j) < 1$ for all $i \neq j$.
- Independent Values (IV): $\rho(\tau_i, \tau_j) = \rho(\eta_i, \eta_j) = 0$ for all $i \neq j$.

In CV, all the firms are subject to a common random parameter, and they observe it with distinct errors. In PS, firms can observe without any error their respective payoff-relevant random parameters which may be correlated with one another. In IV, firms are subject to independent random parameters.

Since the payoff function is quadratic and the random variable is normally distributed in this model, we can explicitly solve for a linear strategy, which is known to be the unique equilibrium, and we can evaluate the size of the equilibrium expected payoff. For all $i \neq j$, we have $\partial^2 \pi_i / \partial s_i \partial s_j = -\epsilon$. Thus ϵ is the parameter expressing strategic complements/substitutes: The game is of strategic substitute variety when $\epsilon > 0$; and of strategic complements variety when $\epsilon < 0$.

The equilibrium of the game and the efficiency of the equilibrium depend both upon the information structure and the strategic nature of the game, *i.e.*, whether it is of strategic complements or strategic substitutes. We state the next proposition without proof.

Proposition 1 (Raith 1996)**.** *In the n-firm two-stage game except for Bertrand competition with cost uncertainty (where $\gamma_n \neq 0$), unilateral information revelation is the dominant strategy for each firm in the independent values (IV), perfect signals (PS) cases, and common value (CV) case with strategic complements. In the common value (CV) case with strategic substitute, nonrevelation is the dominant strategy.*

Furthermore, efficiency is achieved in equilibrium for independent values (IV), perfect signals (PV), and common value (CV) with strategic complements, because the payoffs with complete information sharing are always higher than those without information sharing for these cases. For common value (CV) case with strategic substitutes, information sharing is efficient (resp. inefficient) when there is a large (resp. small) degree of product differentiation.

This result can be intuitively explained as follows. First consider each firm i's unilateral strategic decision. In this case, given the revelation decision by the rivals $j \neq i$, the firm's revelation behavior does not alter the firm's own information. Thus it only matters how the rivals' strategic choice at the second stage change in response to the firm i's revelation. In the cases of independent value (IV) and perfect signals (PS), the revelation of one's own information induces an increase (decrease) in the correlation of strategies with strategic complements (resp. substitutes) and this is the "right" change in that it increases firm i's expected profits. In common value (CV), the revelation of one's information always increases the correlation of strategies, which increases (decreases) expected profits when the game is of strategic complements (resp. substitute).

Next consider whether or not all the firms enter into an *ex ante* agreement to share information, that is, whether or not complete information sharing enhances expected profits of all firms. In the cases of independent value (IV) and perfect signals (PS), information sharing does not increase the precision of one's information, because in independent value (IV) the parameters are independent, and in perfect signals (PS) one's information is completely known. However, information sharing induces "right" change in the correlation of strategies even in those cases, as in the case of unilateral revelation decision. Thus firms agree to share information regardless of the parameter values. In common value (CV) case, information sharing has two effects. On the one hand, by pooling data, it improves the precision of information regarding the common market environment, which always increases expected profits. On the other hand, information sharing in this case always increases the correlation of strategies, which is good for strategic complements and bad for strategic substitute. Thus in the common value (CV) case with strategic substitutes, expected profits can be lower with information sharing if the game has strong substites property.

In sum, whether or not firms have incentives to share information depends on the strategic nature of the oligopoly competition and the structure of information. However, it is remarkable that, in most cases (except for the case of common value (CV) case with strategic substitutes) information revelation is the dominant strategy and sharing information is efficient.

The main shortcoming of this model is that it supposes that firms can commit to its *ex ante* dicision to reveal or not to reveal their information after receiving it. The model seems to describe the situation where firms are engaged in a continual oligopoly competition with random but stationary environmental parameters and consider participating in a trade association which requires participating firms to reveal their information honestly. This interpretation does not seem to fit the firms engagaged in joint R&D efforts.

Another interpretation might be relevant to the R&D context however. Firms involved in joint R&D activities often find it advantageous to share benchmarking information with respect to their technology, because they can learn their relative strength/weakness through the benchmarking information. This phenomenon may be explained with the above result. In the case of Cournot competition with cost uncertainty and with perfect signals (PS), firms find it profitable to share their benchmarking information with one another, because they can fine-tune the second stage strategy by somtimes becoming aggressive and sometimes defensive.

2.2 Strategic Information Revelation and Certifiability

As already noted, the model in Section 2.1 assumes that firms can commit to its *ex ante* revelation decision. However, in most real-world situations, especially when it is related to R&D activities, this assumption seems to be suspicious. The stochastic environments surrounding R&D activities are not stationary and frequently once and for all. Okuno-Fujiwara, Postlewaite and Suzumura (1990) propose and analyze a model in which firms with private information cannot make such an *ex ante* commitment as in the previous model.

Furthermore, the previous model excludes *a priori* the possibility that a firm wants to manipulate its rivals' actions by announcing distorted information. In contrast, Okuno-Fujiwara, Postlewaite and Suzumura (1990) take such a situation into account. Analyzing such a situation enables us to see the difference in outcome between the case where each firm's messages are certifiable and the case where they are not.

Now consider a situation where two firms indexed by $i(=1,2)$ are engaged in a joint R&D investment activity[11]. At the beginning of this game, firm i already has some initial knowledge, the level of which is denoted as w_i, and exerts efforts x_i in this R&D activity, resulting in the final level of knowledge $X_i = w_i + x_i \in \mathcal{X}_i \subset \mathbb{R}$. In what follows, we will take X_i to be the firm i's strategic choice, although we can also take x_i instead. Here $\mathcal{X}_i$ is a compact interval of $\mathbb{R}$. Each firm i chooses the level of X_i knowing its initial knowledge w_i, but not knowing firm j's level of initial knowledge w_j $(j \neq i)$. This is a usual Bayesian game. Folloing the convention in Bayesian game theory, we will sometimes refer to firm i with initial knowledge level w_i as firm i of type w_i or the type w_i of firm i.

The gross payoff to firm i when firm i chooses X_i and firm j chooses X_j is denoted as $v_i(X_i, X_j)$. This can be interpreted either as the gross profit that firm i obtains in the product market competition or as the value of the joint research result for firm i, when the two firms' final knowledge profile is (X_i, X_j). Let the cost of R&D effort $x_i = X_i - w_i$ be $c_i(x_i)$. That is, the net payoff to firm i is written as

$$u_i(X_i, X_j, w_i, w_j) = v_i(X_i, X_j) - c_i(X_i - w_i) \qquad i = 1, 2.$$

We make the following assumption as to the gross payoff and cost functions.

Assumption 1. *For each i, $v_i(\cdot,\cdot)$ is continuously differentiable and has increasing differences in (X_i, X_j) for $j \neq i$[12], and $c_i(\cdot)$ is strictly convex and increasing.*

This assumption implies that $u_i(X_i, X_j, w_i, w_j)$ is (trivially) supermodular in X_i and has increasing differences in $(X_i, (X_j, w_i, w_j))$. The latter means that there is complementarity between X_i and (X_j, w_i, w_j). This condition seems to be satisfied in a usual situation arising in a strategic alliance or a research consortium. In addition, we also assume that the gross payoff functions have positive externalities, that is,

Assumption 2. *$v_i(X_i, \cdot)$ is strictly increasing in X_j.*

These assumptions are satisfied in a usual model with which economists are familiar. For example, suppose that our two firms are engaged in a Bertrand competition following the R&D activities, and that X_i appears in the linear demand function as its intercept. Then the resultant equilibrium payoff in the Bertrand competition has positive externalities as well as increasing differences. Furthermore, this condition seems to be satisfied in usual joint R&D activities.

Recall that the level of initial knowledge w_i of firm i is known to firm i, but is not known to its opponent. Assume that the probability distribution function for w_i (the belief that firm j holds with respect to firm i's initial knowledge level w_i) is discrete. Let its support be $W_i = \{w_i^1, w_i^2, \cdots, w_i^{L_i}\}$ with an order

$$w_i^1 < w_i^2 < \cdots < w_i^{L_i}.$$

[11] The result shown below applies to more general situations. See Okuno-Fujiwara, Postlewaite and Suzumura (1990) and Van Zandt and Vives (2006). The model can be easily extended to an n-firm situation.

[12] If v_i is twice continuously differentiable, this condition is equivalent to $\partial^2 v_i / \partial X_i \partial X_j > 0$ for all distinct i and j.

We denote the belief function that firm i of type w_i holds with regard to the opponent's type by $p_i(w_j|w_i)$[13]. The belief functions are common knowledge. We make the following assumption on the belief functions.

Assumption 3. *$p_i(w_j|w_i)$ is increasing in w_i with respect to the order induced by first-order stochastic dominance. That is, if $w_i' > w_i$, then for all $w_j^k (k = 1, \cdots, L_j)$,*

$$\sum_{w_j \le w_j^k} p_i(w_j|w_i) \ge \sum_{w_j \le w_j^k} p_i(w_j|w_i').$$

This condition is saticefied, for example, when the prior distribution function of the level of knowledge of both firms is affilated[14] *and is trivially saticefied when the prior distribution is independent (that is, if for all k, l, we have $p_i(\cdot|w_i^k) = p_i(\cdot|w_i^l)$).*

A strategy for firm i is $\sigma_i : W_i \to \mathcal{X}_i$. A strategy profile $\sigma^* = (\sigma_i^*, \sigma_j^*)$ is a Bayesian Nash equilibrium if for all i and for all $w_i \in W_i$,

$$\sigma_i^*(w_i) \in \arg\max_{X_i \in \mathcal{X}_i} \left[\sum_{k=1}^{L_j} p_i(w_j^k|w_i) v_i(X_i, \sigma_j^*(w_j^k)) - c_i(X_i - w_i) \right].$$

Note that, by Assumptions 1 and 3, this game is a "monotone supermodular game" defined by Vives and van Zandt (2006), and that there exist a "greatest" and a "least" Bayesian Nash equilibrium, with a partial ordering on the set of strategies defined as $\sigma_i' \ge \sigma_i$ whenever $\sigma_i'(w_i) \ge \sigma_i(w_i)$ for all w_i. Furthermore, in those equilibria, each player adopts a "monotone strategy" meaning that the strategy is increasing in the player's type. That is, for all $w_i' > w_i$, we have $\sigma_i^*(w_i') \ge \sigma_i^*(w_i)$.

Let us now introduce a partial ordering to the set of beliefs such that $p_i' \ge p_i$ if and only if, for all $w_i \in W_i$, $p_i'(\cdot|w_i) \ge p_i(\cdot|w_i)$ holds in the sense of first-order stochastic dominance. Let p and p' be two profiles of beliefs with $p_i' \ge p_i$ for all i and consider two games $\Gamma(p')$ and $\Gamma(p)$ with the same set of parameters (the set of actions and the payoff functions) except for the belief function. By Assumptions 1 and 3, it can be shown that the greatest equilibrium in $\Gamma(p')$ is greater than that in $\Gamma(p)$.

Let us denote the greatest equilibrium in game $\Gamma(p)$ as $\bar{\sigma}(p)$ and the conditional expected utility that firm i of type w_i obtains as $\Pi_i(p, w_i)$. Since $\bar{\sigma}(p)$ is increasing in p_j, $\Pi_i(p, w_i)$ is increasing in p_j by Assumption 2. Namely, firm i of each type can earn higher expected payoff, if the rival has a belief that puts more probability to higher types of firm i.

Intuitively, this can be explained as follows. In this game, since w_i and X_i are complements to each other, higher type w_i of firm i chooses higher X_i (that is, firm i adopts a monotone strategy). On the other hand, since X_i and X_j are complements, firm j optimally chooses a higher level of X_j in response to a higher level of X_i. These together mean that if firm j believes that firm i's type is more likely to be high, firm j chooses to exert higher collaborative efforts. Knowing this, since higher effort by firm j (that results in higher X_j) bring higher payoff to firm i, firm i of any type wants to make firm j to believe that firm i is of a higher type. Thus, firm i has incentives to manipulate firm j's belief, if it is given such an opportunity to do so.

Let us now append to the original game a prestage where each firm, knowing the level of its initial knowledge, can send a message about it. We henceforth refer to this prestage as the first stage of the augumented game and to the original game as the second stage. Let M_i be the set of message firm i can send. We interpret each $m_i \in M_i$ as the set of firm i's types that can send message m_i. We allow for the

[13]This need not be the distribution function derived from a common prior distribution function on (w_i, w_j).
[14]See Milgrom and Weber(1982).

situation that a type of firm i may not want to reveal anything. We do this by including an element m_i that any type can send. Let $M = \prod_{i=1}^{2} M_i$.

In this framework, we can compare the case that each message m_i sent by firm i is certifiable with the case that it is not. Consider first the case the messages are certifiable. That messages are certifiable means that it can be confirmed to be true. However, this does not necessarily means that the opponent's type can be identified by a sent message, because the type may send a message that can be sent by various other types. Furthermore, what kind of message is certifiable usually depends on concrete physical situations. For example, in the present context, it would be difficult to certify that firm i's knowledge level is at most such and such, even if it claims so, while a message meaning that firm i's knowledge level is at least some level can be certified by firm j with enough expertise or by a third party with appropriate judging ability. Thinking in this way, what kind of message is certifiable seems to be determined independent of the game played at the second stage.

In order to show that full revelation arises as an equilibrium outcome when messages are certifiable, we make the following assumption as to the message space.

Assumption 4. *For each $m_i \in M_i$, there exists* $\min m_i$*, and for each w_i, there exists $m_i \in M_i$ such that* $\min m_i = w_i$.

Recall that each m_i means the set of types that can send message m_i. The second assumption means that each type w_i can send a message meaning that it is at least w_i. This assumption describes an aforementioned physical situation concerning what kind of messages are certifiable. In the present context, the first condition means that, for any message, one can identify the minimum knowledge level of the sending firm. The latter condition means any type can send a message that make the opponent to believe it has at least some initial knowlege. These coincide with the situation mentioned above, and so seem to be satisfied in a usual joint R&D activity.

Firm i's strategy at the first stage (reporting strategy) is a mapping $r_i : W_i \to M_i$. Since the messages are certifiable, we assume that $w_i \in r_i(w_i)$ holds for each w_i. This means that each type cannot send a deceptive message, while it can send an ambiguous one. At the beginning of the second stage, each type of firm i updates its belief upon receiving a message profile $m = (m_i, m_j)$. Let this belief updating process be denoted by a belief function $b_i : W_i \times M \to \mathcal{P}_j$, where $\mathcal{P}_j$ is the set of probability distribution over W_j. Again by the certifiability requirement, we may assume that for all $w_i \in W_i$ and all $m \in M$, $b_i(w_i, m)$ puts probability one on $m_j (j \neq i)$. Namely a belief is always updated on the premise that the received message is not deceptive.

The second-stage strategy of firm i is a measurable function $\sigma_i : W_i \times M \to \mathcal{X}_i$. With the first-stage message m given, we have the second-stage belief $b_i(\cdot, m) : W_i \to \mathcal{P}_j$ and the second-stage strategy $\sigma_i(\cdot, m) : W_i \to \mathcal{X}_i$. That is, given message profile m, firms update their beliefs and then play the original Bayesian game with these beliefs. A perfect Bayesian equilibrium is defined to be $(r_i^*, b_i^*, \sigma_i^*)_{i=1}^2$ that satisfy the following conditions:

1. Consistency of Belief: For each i, b_i^* creates a conditional belief function given $(w_i, (r_j^*(w_j)))$ by Bayes-updating the original belief wherever possible.

2. Equilibrium at the second stage: For each $m \in M$, $\sigma^* = (\sigma_i^*(\cdot, m), \sigma_j^*(\cdot, m))$is a Bayesian Nash equilibrium of the game $\Gamma((b_i^*(\cdot, m))_{i=1}^2)$.

3. Equilibrium at the first stage: For each i and each $w_i \in W_i$,

$$r_i^*(w_i) \in \arg \max_{m_i \in M_i : w_i \in m_i} \sum_{w_j} p_i(w_j | w_i) u_i(\sigma_i^*(w_i, (m_i, r_j^*(w_j))), \sigma_j^*(w_j, (m_i, r_j^*(w_j))), w_i, w_j).$$

Under these settings, the next proposition holds.

Proposition 2 (Okuno-Fujiwara, Postlewaite and Suzumura 1990)**.** *Suppose that Assumption 4 holds for the messages. Let* $b_i^* : W_i \times M \to \mathcal{P}_j$ *denote a belief formation function such that* $b_i^*(w_i, m)$ *gives probability one on* $\min m_j$ *for all* $w_i \in W_i$ *and for all* $m \in M$*. Also, let* $r_i^* : W_i \to M_i$ *be such that* $w_i = \min r_i^*(w_i)$ *for all* w_i*. Furthermore, let* $\sigma^*(\cdot, m)$ *be a greatest Bayesian Nash equilibrium of the game* $\Gamma((b_i^*(\cdot, m))_{i=1}^2)$*. Then* $(r_i^*, \sigma_i^*, b_i^*)_{i=1}^2$ *is a perfect Bayesian Nash equilibrium.*

Proof. The messages are fully revealing, since r_i^* is such that $w_i \neq w_i'$ implies $r_i^*(w_i) \neq r_i^*(w_i')$. As b_i^* correctly forms belief for all equilibrium messages, the b_i^* satisfies consistency. Since the strategy profile σ^* is Bayesian equilibrium of the $\Gamma((b_i^*(\cdot, m))_{i=1}^2)$, it suffices to show that the message strategy maximizes expected payoff. The situation in this game is that where each type of each player wants the other player to believe his type to be as high as possible. However, by the certifiability assumption, it must be that $w_i \in m_i$. Given the skeptical beliefs b_j^*, it is optimal for type w_i to send a message such that $w_i = \min m_i$. □

With some additional technical conditions, it can also be shown that full revelation is essentially the unique equilibrium outcome. Let us now turn to the case that messages are not certifiable. In this case, firm i can send an arbitrary message in M_i. This undermines the credibility of sent messages completely. The next proposition holds in this case.

Proposition 3. *When messages are not certifiable, the messages in the first stage convey no information at any perfect Bayesian Nash equilibrium.*

Proof. We first show that full revelation is not achieved. Suppose $(r_i, b_i, s_i)_{i=1}^2$ is a perfect Bayesian equilibrium that is fully revealing. If the smallest type w_i^1 of firm i sends a message $r_i(w_i^2)$, then it causes a shift in firm j belief from his being of type w_i^1 with probability 1 to his being of type w_i^2 with probability 1. Hence, his expected payoff can strictly increase. This contradicts the assumption that $(r_i, b_i, s_i)_{i=1}^2$ is a perfect Bayesian equilibrium.

If some message is informative, there exists a proper subset S of firm i's types such that firm j put probability 1 on the set with this message. Since all the messages are not fully revealing, there exist more than one type in this set. If there exists some type w_i such that $\min S > w_i$, this type can strictly increase his expected payoff by sending the same message with the set. Suppose then that the set contains lowest types. In this case, those types can earn higher expected payoff by sending a message that a higher type that is not in the set is sending. This is a contradiction. □

The discussion thus far can be summarized as follows:

1. Under the three conditions regarding the structure of our joint R&D game that follow, there arises a situation where each type w_i of each firm i wants to induce its rival to hold a higher belief that puts more probability to higher types;
   (a) X_i and X_j are complements;
   (b) X_i and w_i are complements; and
   (c) X_j has a positive externality for firm i;
2. With two additional conditions regarding certifiability of messages that follow, each firm fully reveals its type in equilibrium;
   (a) The messages sent prior to the joint R&D process is certifiable; and

(b) The structure of certifiability is such that message allows the receiver to identify the smallest type that can send the message.

Let us add some explanation as to why the second set of conditions is required and how it works. Suppose for example a situation where two firms are competing in a market of homogeneous goods with a linear demand curve and are playing a quantity-setting Cournot game. The constant marginal cost of firm 1 is random and assume the value of either c_1^H or c_1^L with $c_1^H > c_1^L$. We call the type of firm 1 with marginal cost c_1^H "H-type" and c_1^L "L-type." Not knowing firm 1's type, firm 2 has to choose its output in optimal response to the expected output of firm 1. In such a situation, type L of firm 1 want to reveal its type, because it can induce firm 2 to reduce output and thereby increase its profit if firm 2 believes it is indeed type L. Suppose that the set of message is structured as $\{\{H\}, \{H, L\}\}$. Then Both H-type and L-type will send a certifiable message $\{H, L\}$ (recall that certifiable message has to contain the true type), so that the message cannot convey any information. If the message space is $\{\{L\}, \{H, L\}\}$, then type L will send message $\{L\}$ that only type L can send and firm 2 will identify type L. At the same time, firm 2 will successfully identify type H, because type H's certifiable message $\{H, L\}$, meaning "I don't want to be identified," is different from type L's.

Does the full revelation bring higher expected profit to the firms? The model in this subsection is more general than the model in Section 2.1., but we can specify the payoff function so that the efficiency result in Proposition 1 can be applied. For example let $v_i(X_i, X_j) = \frac{1}{4}X_iX_j, c_i(X_i - w_i) = (X_i - w_i)^2$. This belongs to the class of payoff functions examined in Section 2.1. Just let $\tau_i = w_i$ and $s_i = X_i$ in (1), and let $\alpha(w_i) = -w_i^2, \beta_n = \gamma_n = 0, \epsilon = -1/4, \beta_s = 0, \gamma_s = 2, \delta = 1$ for the other parameters. Since the type of information structure in this model is perfect signals (PS), an equilibrium with full revelation is *ex ante* efficient for both firms.

Finally we would like to add that the analysis in this subsection suggests the necessity of an agent who ensures unbiased information exchange. Only under the assumption that messages are certifiable, firms cannot send a deceptive message (firm i of type w_i cannot sent m_i with $w_i \notin m_i$) and the firm receiving the message m_i can put probability 1 on m_i. This condition can be best fulfilled by the existence of a neutral third party who has enough expertise to evaluate the firms' messages and communicates the information to the other firms without distortion. Thus, the analysis in this subsection suggests that the involvement of a neutral third party is necessary in a research consortium, where the degree of uncertainty seems to be higher than in a strategic alliance, as pointed out by Chuma (2003).

3 The Impact of Information Sharing on Incentives in Ongoing R&D

In the previous models, the information to be shared/revealed is that about exogenous parameters, such as uncertain cost or demand parameters. This type of information is that which cannot be controlled by firms, but should be shared for initiating a new project. In a ongoing joint R&D process, however, firms are continually creating new knowledge over time, and sharing the *interim* research results also seems to be important for successful completion of the project. In this section, we consider how the sharing of ongoing research results affects the incentives of firms engaged in collaboration.

Suppose again that two firms ($i = 1, 2$) are engaged in a collaborative R&D activity over two periods and choose the level of R&D investment simultaneously and independently. The payoff to firm i is

$$\begin{aligned}\Pi_i(\mathbf{x}_1, \mathbf{x}_2) &\equiv V_i(\mathbf{x}_1, \mathbf{x}_2) - C_i(\mathbf{x}_1) \\ &\equiv V_i(x_1^1, x_2^1; x_1^2, x_2^2) - C_i(x_1^1, x_1^2).\end{aligned} \tag{2}$$

where x_i^t denotes the investment of firm i in period t, $\mathbf{x}_i = (x_i^1, x_i^2)$ is the investment profile of firm i over two periods, $V_i(\cdot, \cdot)$ is the gross profit obtained from the research results, $C_i(\cdot)$ denotes the cost of research activity.

Using this model, let us examine the impact of the *interim* information sharing on the firms' R&D investment levels. Suppose that an evaluator acts as such an information mediator. Without such an evaluator, firm i cannot know the content or value of the investment made by firm $j(\neq i)$ untill the end of the second period. Thus the firm i has to choose its second period investment x_i^2 without knowing x_j^1. On the other hand, with an evaluator who examines information and make it common knowledge to all the firms, firm i knows x_j^1 when it chooses x_i^2 at the beginning of the second period. Therefore, firm i can condition its second-period investment level x_i^2 on $\mathbf{x}^1 \equiv (x_1^1, x_2^1)$.

Firms $i = 1, 2$ are playing a noncooperative game aiming to maximize their respective payoffs over two periods, In terms of game theory, an open-loop Nash equilibrium is realized without any evaluator, while a closed-loop Nash equilibrium is realized with an evaluator.

When there is no evaluator, a Nash equilibrium is an investment decision profile $(\mathbf{x}_1^{**}, \mathbf{x}_2^{**})$ that satisfies the following four conditions:

$$\frac{\partial V_i(\mathbf{x}_1^{**}; \mathbf{x}_2^{**})}{\partial x_i^t} - \frac{\partial C_i(\mathbf{x}_i^{**})}{\partial x_i^t} = 0 \qquad \forall i = 1, 2,\ t = 1, 2. \tag{3}$$

When there is an evaluator who evaluates investments made in the first period and makes the information common knowlege, firms $i = 1, 2$ know the realization of $\mathbf{x}^1 \equiv (x_1^1, x_2^1)$. Therefore a Nash equilibrium in the second period satisfies

$$\frac{\partial V_i(\mathbf{x}^1; x_1^2, x_2^2)}{\partial x_i^2} - \frac{\partial C_i(x_i^1, x_i^2)}{\partial x_i^2} = 0 \qquad \forall i = 1, 2. \tag{4}$$

Since the equilibrium depends on the realized investment profile $\mathbf{x}^1$, let this equilibrium be denoted by $\mathbf{x}^{2*}(\mathbf{x}^1) \equiv (x_1^{2*}(\mathbf{x}^1), x_2^{2*}(\mathbf{x}^1))$.

Expecting that the above outcome realizes in the second period, the payoff function to be maximized in the first period is

$$V_i(\mathbf{x}^1, \mathbf{x}^{2*}(\mathbf{x}^1)) - C_i(x_i^1, x_i^{2*}(\mathbf{x}^1)). \tag{5}$$

By the envelope theorem, *i.e.* using (4), the first-order conditions for the first-period investment must satisfy:

$$\frac{\partial V_i(\mathbf{x}^1, \mathbf{x}^{2*}(\mathbf{x}^1))}{\partial x_i^1} + \frac{\partial V_i(\mathbf{x}^1, \mathbf{x}^2(\mathbf{x}^{1*}))}{\partial x_j^2}\frac{\partial \mathbf{x}_j^{2*}(\mathbf{x}^1)}{\partial x_i^1} - \frac{\partial C_i(x_i^1, x_i^{2*}(\mathbf{x}^1))}{\partial x_i^1} = 0 \qquad \forall i = 1, 2. \tag{6}$$

Thus, with an evaluator, a Nash equilibrium is an investment profile $(\mathbf{x}^{1*}, \mathbf{x}^{2*}) = (x_1^{1*}, x_2^{1*}, x_1^{2*}, x_2^{2*})$ that satisfies (6) and (4) simultaneously.

Comparing equation (6) with equation (3), we see the difference of equilibrium conditions lies in the existence of the second term in equation (6), which is usually called the "strategic effect." This term is a product of $\partial V_i/\partial x_j^2$ and $\partial x_j^{2*}/\partial x_i^1$ and it is easy to see that there are two cases that this term becomes positive.

Let us say that the second-period investment exerts positive (negative) externality when $\partial V_i/\partial x_j^2$ is positive (resp. negative) for all i and all $i \neq j$ and that the dynamic game is investment-inducing (investment-reducing) when $\partial x_j^{2*}/\partial x_i^1$ is positive (resp. negative) for all i and all $i \neq j$. Then the two cases that give rise to a positive strategic effect are:

(1) The case where second-period investment exerts positive externality and the dynamic game is investment-inducing; and

(2) The case where second-period investment exerts negative externality and the dynamic game is investment-reducing.

The sign of $\partial x_j^{2*}/\partial x_i^1$ is determined by and equal to the sign of the cross derivative $\partial^2 \Pi_j/\partial x_i^1 \partial x_j^2 = \partial^2 V_j/\partial x_i^1 \partial x_j^2$. This is positive if V_j has increasing differences in $(\mathbf{x}_1, \mathbf{x}_2)$, namely the investment levels made by firm i and firm j are complements to each other.

We think that usual situations arising in research consortia correspond to the first case above with positive strategic effects; Second-period investment exerts positive externality and the dynamic game is of the investment-inducing kind. The second case that the strategic effects are positive is the one where second-period investment exerts negative externality and the dynamic game is investment-reducing. This situation arises when part suppliers are engaged in a tournament game competing for delivering a part to an assembler. See Konishi, Okuno-Fujiwara and Suzuki (1996) for the analysis of this case.

Let us now regard the left-hand side of equation (6) and equation (3) as functions of x_i^1. Due to the second-order conditions, those functions are decreasing in x_i^1. Thus, if the strategic effect is positive, then we have

$$x_i^{1*} > x_i^{1**}.$$

Namely, we have shown that, in the standard case of research consortium, both firms' equilibrium investment levels are increased if an evaluator evaluates their *interim* investment levels from a neutral standpoint and make them common knowledge to the participants.

The model in this section has shown that the presence of an evaluator can exert a positive effect on firms' incentive to make efforts in a joint R&D activity by changing the strategic nature of the game. We conjecture that the model can be changed and/or extended without changing the basic result. First, we may change the above game so that the firms move sequentially rather than simultaneously without changing the basic result. Second, it may be that the evaluator does not have to see the investment levels in the first period completely accurately as in the above model. As long as the evaluator makes the information concerning $\mathbf{x}^1$ more accurate, say by reducing noises, his presence will have an impact on the level of investments.

Some more interesting questions awaits further exploration in relation to this model. First, it would be interesting to examine how the investment level changes when we increase the frequency of *interim* information exchange. Second, we may be able to integrate this model with the model in Section 2.2 by incorporating initial level of knowledge w_i for each firm i and allowing it to reveal this private information. In that case also, it is conjectured that full revelation equilibrium obtains if the revelation is investment-inducing. Third, it would be interesting to examine the firms' incentives to reveal their first-period investment levels honestly, when they are allowed to send messages regarding this information. Finally, in view of the importance of the evaluator's role, his incentive to do the job correctly should be explored.

4 Conclusion

In the recent changes of economic environments, firms are increasingly engaged in across-firm collaborative R&D activities in the form of a research consortium and/or a strategic alliance. Those processes can often be conflict-ridden, and will not be successful unless the participating firms have enough incentives to reveal their private information that is relevant to the collaborative process and to exert sufficient efforts. The present paper attempts to explore the conditions under which firms have enough incentives to reveal their information and/or to expend collaborative efforts, examining three existing economic models.

What implications for the effective joint R&D activity can we draw from the examination of these models? First, the models we discussed enable us to identify rigorous conditions under which firms have incentives to reveal their information and/or to exert collaborative efforts in respective models. To the extent that those models reflect reality, those conditions are relevant to the successful collaborative R&D activities. The incentives to reveal their information and/or to exert collaborative efforts are shown to depend largely on the nature of the oligopolistic game firms play (strategic substitutes/strategic complements or positive externality), information structure of the firms' private signals (common value, perfect signal, independent values), and how the private information affects the firms' payoffs in the game (complements/substitute). Roughly put, when the firms' R&D efforts are advantageous to each other, then we can find some mechanism to induce their efforts. However, it has also be shown this is not sufficient.

Second, and more importantly, as suggested by the models in Section 2.2 and Section 3, it is necessarily that information revealed by firms is correctly evaluated and communicated to the others without distortion. Without any mechanism to ensure such unbiased information exchange, the incentives for truth-telling and making appropriate efforts might be severely impaired. The existence of such a mechanism seems to be the key to successful collaboration.

When the conflict of interests between firms can be complex, the role of information mediation may best be played by a third party. Then the third party should fulfill two requirements. On the one hand, it has to have enough technological expertise to appropriately evaluate the technological information revealed by each participating firm. On the other, it should be neutral to the extent that all the participating firms believe it not to convey distorted information.

Third, if some deviation from the model analyses is permitted, we would like to add that the third party above has another important role to play. The alignment/disalignment of interest among firms can be sometimes so complex that firms may not be able to grasp the situation they face correctly, while, in the models examined so far, firms exactly know the complementarity/substitute parameters. In such cases, if the third party is trusted by all firms and can collect enough payoff-relevant information from them, it can act as a kind of matchmaker to help firms exploit profit opportunities.

Despite our emphasis on the important role that can be played by the third party, we have not considered the third party's incentives in this paper. Furthermore, we may be able to integrate and extend the models in Section 2.2 and Section 3 to consider firms' incentive to reveal information as to their initial level of knowledge and/or *interim* accumulated knowledge levels. We would like to leave those issues for the subjects of another paper.

Bibliography

Chuma, H. (2003), "Determinants of Microlithography Industry Leadership: The Possibility of Collaboration and Outsourcing," RIETI Discussion Paper Series 03-E-003.

Konishi, H., M. Okuno-Fujiwara and Y. Suzuki (1996), "Competition through Endogenized Tournaments: An Interpretation of 'Face-to-Face' Competition," *Journal of the Japanese and International Economies*, Vol. 10, pp.199-232.

Lamoreaux, N.R. and D.M.G. Raff and P. Temin (2003), "Beyond Markets and Hierarchies: Toward a New Synthesis of American Business History," *American Historical Review*, Vol.108, pp.404-433.

Milgrom, P.R. and R.J. Weber (1982), "A Theory of Auctions and Competitive Bidding", *Econometrica*, Vol. 50, No. 5, pp. 1089–1122.

Okuno-Fujiwara, M., A. Postlewaite and K. Suzumura (1990), "Strategic Information Revelation," *The Review of Economic Studies*, Vol.57, No.1, pp.25-47.

Raith, M. (1996), "A General Model of Information Sharing in Oligopoly," *Journal of Economic Theory*, Vol. 71, pp.260-288.

Sabel, C. F. and J. Zeitlin (2004), "Neither Modularity nor Relational Contracting: Inter-Firm Collaboration in the New Economy," *Enterprise and Society*, Vol.5, pp.388-403.

Vives, X. (1999), *Oligopoly Pricing: Old Ideas and New Tools*, Cambridge, Massachusetts, The MIT Press.

Van Zandt, T. and X. Vives (2007), "Monotone Equilibria in Bayesian Games of Strategic Complementarities," *Journal of Economic Theory*, forthcoming.