On Information Sharing And Incentives in R&D

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Abstract

Firms competing in the R&D frequently have to deal with the problem of possible exchange of information between their employees. Direct methods of control over such information exchange are often ineffective. In this paper we demonstrate how firms can use the incentive schemes to regulate these information flows. The optimal incentive schemes are derived and properties of equilibria of the incentive scheme game between firms are characterized for different payoff configurations. The results provide an explanation for an observed diversity of incentives schemes for engineers and other technical employees, and for the use of stock options and other forms of profit sharing as a method of preventing the information exchange. We demonstrate that free-riding by both the firms and employees has a significant impact on the final outcomes.

1 Introduction

Both casual observation and empirical evidence suggest that exchange of technological information between engineers and scientists employed by different firms is a common and wide-spread phenomenon. In a number of studies it was found to play an important role in the development and dissemination of technical knowledge. Von Hippel [27] reports that informal know-how trading is quite intensive in the aerospace industry, waferboard manufacturing and steel minimill industry in the U.S. According to Rogers [22], exchange of information between employees of different firms constitutes "a dominant and distinguishing characteristic of the environment" in the microprocessor and solar flat-plate collector industries in the Silicon Valley. Schrader [25] has found that information received from colleagues working for other firms ranked as the second most important source of technical knowledge in the steel mini-mill industry. Only information obtained from colleagues within the same firm was seen on average to be more important. Schrader reports that 85 % of all respondents to his survey of technical managers from the industry had been asked for specific technical information by employees working for other firms, and only 2 percent had never provided the requested information.

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Along with the evidence confirming the significance of the information exchange, there is also sufficient evidence showing that direct ways of controlling and/or preventing this exchange, such as patents and trade secrets policies, are often ineffective. In the already cited study Rogers [22] concludes that "patents are not an effective means of preventing information exchange..." in the microprocessor and solar industry. Two problems significantly reduce the applicability of patents. First, patenting an innovation involves its public disclosure and makes it vulnerable to 'inventing around'- copying an innovation in a modified form. Second, new patents frequently cannot be exercised without infringing on the claims of other patents. Consequently, a firm might not be able to use its innovation, or else will be forced to cross-license it with other firms holding related patents.

At the same time, the use and the scope of the trade secrets policy is limited because of the inability of the courts to establish a clear and unambiguous criterion distinguishing an employer's 'know-how' protected as a 'trade secret' from employees' general knowledge which they are free to discuss and disseminate (cf. [7]). This task turned out to be hard for the courts, because they have to maintain a very delicate balance between the interests of the firms in appropriating innovations and the right of employees to use their knowledge and skills. In practice, contracts restricting an employee from the participation in the main forms of scientific communication are impossible to enforce in court (and may not even be desirable from the firm's point of view, if such communication helps to enhance the employees' productivity, morale, or job prospects). Moreover, employees can use different strategies to circumvent the companies' secrecy policies. Rogers [22] points out that "almost every secrecy norm for technological information exchange in a high-technology industry has an equally well-known form of evasion".

In the absence of direct methods of control over the exchange of information, firms can only regulate the information flows by providing appropriate incentives to the employees. Consequently, the compensation schemes offered by the firms have to perform two functions: first, induce the employees to take the effort, second, prevent (induce) information exchange.

The design of the optimal incentive schemes is studied in this paper. We characterize the optimal incentive schemes and demonstrate how they can be used to achieve these two goals, and then proceed to describe the equilibrium outcomes in the incentive scheme game between the firms. This task turns out to be quite complex, particularly, because an employee's optimal actions depend not only on the incentive scheme offered by her employer, but also on the expected actions of the employees of the other firms.

The model which I utilize to study these issues has a number of standard features of the agency literature, as well as several non-standard ones. The firms operate in a duopolistic market and have an agency structure. They are subject to dual moral hazard: as employee's effort as well as her participation in the information exchange with an employee of the other firm are not observable. In modeling the information exchange, I postulate simple rules of behavior described in the empirical literature (besides the already-mentioned authors, see also Saxenian [24]):

- Firms have little or no direct control over the information exchange between the employees, because of a large number of communication channels available to the latter (including conferences, trade shows, electronic and published media) and because the standard of 'protected information' is difficult to establish.

- Reciprocity: information can only be exchanged, and cannot be bought or sold.
- Information is more readily revealed to a party that is more likely to have a high degree of technical knowledge and provide useful information in exchange.
- At the time of exchange, the value of information is uncertain.

One of the first results in the paper demonstrates that in order to prevent an employee from participating in the information transmission, the firm has to offer rewards contingent on the quality of the products developed by both her and competitor's employees, i.e. use the peer-comparison. Direct forms of peer-comparison are rarely seen in the real world. However, the common methods of compensating engineers through incentive stock options and other forms of profit sharing can be seen as such, since their actual payoff is determined by the firm's profitability, which in turn depends on the quality of the products offered by both firms. Thus, our results provide a new explanation of the practice of using stock options and profit sharing schemes as a method of preventing information exchange between employees of different firms. Surprisingly, the optimal incentive schemes designed to induce information transmission will typically incorporate some elements of peer comparison as well, but for a different reason: to reduce the cost of inducing effort by offsetting the agent's free-riding.

Thus, our results demonstrate that it is not necessarily optimal to reward an employee exclusively on the basis of her own productivity, even when its precise measure is available. Doing so leads to the information exchange between the employees, and furthermore, causes them to free-ride and exert less effort. On the other hand, the use of the stock options and other methods of profit sharing, the payoffs from which reflect the contributions of a larger group, allows to avoid these problems. Thus, the common intuition that compensation based on measures of group performance leads to free-riding is not always correct.

The equilibrium analysis of the incentive scheme game between the firms is quite complex because of the interaction between effects of the two incentive schemes. An employee's optimal actions depend non only on the incentive scheme offered to her, but also on the expected actions of the other employee, and hence on the incentive scheme offered by the other firm.

Several factors determine whether a firm attempts to prevent or encourage the information exchange. Preventing the information exchange may be useful for two reasons. First of all, it reduces the spillover of technological information to the competitor, making it possible for a firm to attain technological leadership. Secondly, it eliminates an employee's free-riding. When employees exchange information, their incentives to exert effort are diminished because they can rely on the information obtained from the others. Then a firm has to offer more high-powered and costlier incentive schemes to induce the desired amount of effort.

On the other hand, the provision of incentives for an employee not to take part in the information exchange increases the firm's cost of compensation. Additionally, because the exchange of information has to be mutual, the firm can free-ride and save the cost of preventing its employee from participating in this exchange, if it expects that the other firm will offer such incentives to its employee. Further, a firm may have a strategic interest in inducing information exchange as a way to learn about the innovations developed by the others. This consideration turns out to be quite important when firms are not competing in the same market, for example, when they operate only on the national markets of two different countries.

Obviously, which of the above factors are stronger and hence whether in equilibrium the information exchange takes place or not depends on the nature of the firms' interaction in the product market. We demonstrate that, not surprisingly, the information exchange is prevented with a positive probability when attaining the technological leaderhsip is valuable. This probability goes to zero as the payoff to technological leadership becomes very significant. In the latter case, one of the firms prevents its employee from the participation in the information exchange, while the other firm free-rides and saves the cost of offering these incentives. It rewards its employee exclusively on the basis of the quality of her product. This case illustrates another general property of our model: all pure strategy equilibria are asymmetric. Thus, we can use our results to explain why a wide variety of incentive schemes for engineers and technical employees are used in the same industry.

More surprisingly, the information transmission is also prevented with probability 1 when there are large spillover effects and the use of an innovation cannot be appropriated, which happens, for example, when one firm can immediately and almost costlessly imitate the product offered by the other firm. In this case information exchange between the employees does not provide any benefits to the firms, while preventing it reduces a firm's cost of inducing effort by eliminating employee's free-riding.

An important case where the information exchange does occur is the one where a firm's payoff depends only on the quality of its product, which may be true if the firms are operating in different markets (regions). Firms have a strategic interest to induce the information sharing and through it to learn about the innovaions developed by the other firms.

Using the continuity to extend the results which are obtained for the special cases, we can conclude that the firms generally allow the information exchange to occur with some probability, when the competition in the product market is not too intensive. In this way, they decrease the cost of compensation and also hope to free-ride on the incentive provided by the competitor. However, the lack of coordination in the mixed strategy equilibria leads to the to the excessive rates of information exchange between the employees.

This paper makes a contribution to the literature on rivalrous agency, which, among others, includes the works of Fershtman and Judd [8], [9], Katz [15], Spencer and Brander [26]. Several papers in this literature, in particular, [8] and [9] and [26], have demonstrated that in the situation of competition between several agencies the principals can improve their payoffs by offering such contracts to the agents, that make them act either more or less agressively in the final stages of the game. The situation considered here is different, because the principals compete in the product market directly, while agents' participation is necessary in the earlier stages when the R&D is performed. The rivalrous agency problem arises due to the interaction between the agents, who can collude/cooperate and undertake actions which will harm either one or both principals. In modeling the contract offer game, we share the view of Katz [15] that these contracts cannot be credibly commited to because of the possibility of secret renegotiation. Thus, the contracts are not observed by the outside parties and cannot be used as a credible signal to the other agency.

This paper is also related to the literature on cooperation between agents, in partiular Holmstrom and Milgrom [11], Itoh [12], [13], Macho-Stadler and Pérez [18], Ramakrishnan and Thakor [20]. As those authors, we find that it is optimal to use relative performance comparison in the structure of the incentive schemes. However, we demonstrate that the relative performace comparison will be used not only to induce cooperation, as shown by these authors, but also to prevent cooperation/collusion between agents.

The rest of the paper is organized as follows. In section 2 the model is developed, in section 3 optimal incentive schemes are characterized, and in section 4 the existence of equilibrium is established and equilibrium outcomes are characterized in a number of special cases.

2 Model

Two firms indexed by A and B operate in the market for one product. Each firm hires an agent (an engineer or researcher) to undertake R&D and design/develop a new version of the product. The agent is referred to as 'she' and indexed by A or B. The new product can be either of high quality (indexed by θ_2) or low quality (indexed by θ_1). Firms are risk-neutral and agents are risk-averse. If we define a state of the world as a pair of qualities of the products delivered by the firms (the first (second) element in the pair stands for the quality of firm A's (B's) product), then the firms' payoffs can be represented in the following table:

State of The World	Payoff to firm A	Payoff to Firm B
(θ_2, θ_1)	π_{21}	π_{12}
(θ_1, θ_2)	π_{12}	π_{21}
(θ_2, θ_2)	π_{22}	π_{22}
(θ_1, θ_1)	π_{11}	π_{11}

We will assume the following restrictions on the ordering of the payoffs:

$$\begin{cases} \pi_{22} > \max\{\pi_{22}, \pi_{12}\} \\ \pi_{22} > \pi_{11} \\ \pi_{21} - \pi_{11} \geq \pi_{22} - \pi_{12} \end{cases}$$

The probability p $(q) \in [0,1]$ that the product developed by the agent A (B) is of high quality depends on the effort taken by this agent. The effort is costly and is not observable and hence not contractable. Employing a suitable reparameterization, I assume that agents choose the probabilities p and q directly, instead of choosing effort. Let $D(p)$ $(D(q))$ denote the cost to agent A (B) of effort/probability p (q). I assume that $D(.)$ has the following properties: $\forall p \in [0,1]$ $D(p) \geq 0$, $D'(p) > 0$, $D''(p) > 0$, $D(0) = 0$, $D'(0) = 0$. To guarantee an interior solution, we will assume that $\lim_{p \to 1} D'(p) = \infty$. This assumption implies that $\exists \hat{p} \in (0,1)$ s.t. $D'(\hat{p}) = \pi_{21} - \pi_{11}$.

Whether the agent designs the high-quality product or not, the low quality design θ_1 is always available to the firm either because the firm possesses the low quality design and the agent is hired to produce the high quality innovation, or alternatively, because producing the low quality design requires no effort on the part of the agent, or else a fixed and verifiable amount of effort. In the latter case the firm can ensure that the agent develops at least the low quality design by imposing large penalties on the agent if she fails to do so. The two interpretations lead to identical conclusions, and either of them fits the model equally well.

The agents are risk-averse and have identical utility functions $u(w) - D(e)$ separable in the income w and effort e. The income utility function $u(.)$ is three-times continuously differentiable, strictly increasing and concave. Under these assumptions, the inverse utility function (or expenditure function) $h(s) = u^{-1}(s)$ is well-defined, increasing and convex and measures the monetary cost of providing utility s to the agent. I assume that $h'(0) > 0$.

The reservation utility of an agent is equal to $\underline{u} \geq 0$. I assume that $\underline{u}$ is not too large in the following sense: $\exists \epsilon > 0$, s.t.

$$(\pi_{22} - \pi_{11})(1 - \hat{p})\epsilon > h\left(D(\epsilon) + \underline{u}\right)$$

Consequently, each firm will induce its agent to take a positive effort, and there is no equilibrium in which R&D is performed only at one of the firms. It also follows that a firm will not use the low quality design when the high quality design is available.

The timing of events is the following. At first, each firm offers an incentive scheme to its agent. An incentive scheme offered by one firm is not observed by the other firm, or its agent. Then the agents take efforts and develop methods of the product design. After that, without observing the other agent's effort, each agent decides whether she wants to exchange her information with the other agent or not. If both of them have agreed upon it, the information exchange takes place. I assume that the research information is 'hard' and cannot be distorted or disclosed only partially: an agent can disclose either none or all of it to the other agent. Finally, each agent transfers the information that she has to her firm. This information is tested, and it is revealed whether it contained a high quality or a low quality design.

The R&D process and information exchange can formally be represented in the following way. There is a set of possible products Ω (of measure 1). Each element ω of this set represents a different product. The high quality product $\bar{\omega}$ is unique. However, each ω is equally likely to be the high quality product. In the first stage, agent A(B) develops methods of designing products in some subset of measure p (q) at cost $D(p)$ ($D(q)$). Next, if the agents agree to exchange information, each of them transfers all the designs that she had developed to the other. Thus, the agents have identical information after the exchange, and will both either fail or succeed in delivering the high quality design, with the probability of success being equal to $1 - (1 - p)(1 - q)$. Stated differently, the benefit of information exchange for each agent consists of acquiring the 'second shot' at a high quality product.

Notice that the information sharing has to be mutual, and it occurs only if both agents have agreed upon it. I assume that the information cannot be either sold or bought. The assumption that the information is 'hard' and cannot be distorted or disclosed partially can be justified on the grounds that either the distortions are too costly as they require running a duplicate set of experiments, or that the each agent learns the effort of the other agent if the exchange of information has been agreed upon. The assumption that exchange of information takes place at the interim stage (after an agent has exerted the effort, but before she has learned whether she has designed a high quality product or not), is consistent with the empirical observation that such exchanges normally take place when the new technologies are at the early stages of development, and their value at that point is uncertain. It takes time to process information collected by a researcher, adjust it to the market requirements, and learn the quality of her innovation.

I will now turn to the description of the set of possible actions of all parties in this situation. I assume that a payment to the agent can be contingent upon the state of the world, i.e. qualities of the products that are sold by both firms in the market (but a firm cannot contract with the agent working for the other firm). Thus, incentive scheme offered by the firm A (firm B) can be represented as a 4-tuple of utility levels $(v_{21}, v_{22}, v_{12}, v_{11})$ (respectively, $(u_{21}, u_{22}, u_{12}, u_{11})$). The cost to the firm of providing utility level v to its agent is $h(v)$. The following matrix summarizes the payoff structure:

State of the World	Payoff to Agent A	Payoff to Agent B
(θ_2, θ_1)	v_{21}	u_{12}
(θ_1, θ_2)	v_{12}	u_{21}
(θ_2, θ_2)	v_{22}	u_{22}
(θ_1, θ_1)	v_{11}	u_{11}

The strategy of agent A (B) consists of a pair $F_A(p), \delta(p)$ $(F_B(q), \sigma(q))$, where $F_A(p)$ $(F_B(q))$ stands for the probability distribution over effort levels, and $\delta(p)$ $(\sigma(q))$ is the probability that agent A (B) agrees to share information after she has taken effort p (q). Then the expected efforts of agents A and B are equal to $barp = \int_0^1 p dF_A(p)$ and $barq = \int_0^1 q dF_B(q)$ respectively, while the probability that agent A (B) agrees to share information is equal to $d\bar{e}lta = \int_0^1 \delta(p) dF_A(p)$ $(\bar{\sigma} = \int_0^1 \sigma(q) dF_B(q))$. Conditional on her decision to share information, agent A(B)'s expected effort is equal to:

$$\bar{p}^c = \frac{\int_0^1 p\delta(p)dF_A(p)}{\int_0^1 \delta(p)dF_A(p)} \qquad \left(\bar{q}^c = \frac{\int_0^1 q\sigma(q)dF_B(q)}{\int_0^1 \sigma(q)dF_B(q)}\right)$$

Conditional on her decision not to share information, agent A(B)'s expected effort is equal to:

$$\bar{p}^{nc} = \frac{\int_0^1 p(1-\delta(p))dF_A(p)}{\int_0^1 (1-\delta(p))dF_A(p)} \qquad \left(\bar{q}^{nc} = \frac{\int_0^1 q(1-\sigma(q))dF_B(q)}{\int_0^1 (1-\sigma(q))dF_B(q)}\right)$$

When agent B is expected to follow the strategy $(F_B(q), \sigma(q))$, then agent A gets the following expected payoffs if she takes an effort p: i) when agent A refuses to share information:

$$p\bar{q}v_{22} + p(1-\bar{q})v_{21} + (1-p)\bar{q}v_{12} + (1-p)(1-\bar{q})v_{11} - D(p) \tag{1}$$

ii) when agent A agrees to share information:

$$\begin{aligned} &\bar{\sigma}[(1-(1-p)(1-\bar{q}^c))v_{22} + (1-p)(1-\bar{q}^c)v_{11}] \\ &+ (1-\bar{\sigma})[p\bar{q}^{nc}v_{22} + p(1-\bar{q}^{nc})v_{21} + (1-p)\bar{q}^{nc}v_{12} + (1-p)(1-\bar{q}^{nc})v_{11}] - D(p) \end{aligned} \tag{2}$$

Notice that A's expected payoffs expressed in (1) and (2) are strictly concave in p and depend on the actions of the agent B only through $\bar{q}^c$, $\bar{q}^{nc}$, and $\bar{\sigma}$.

Let p^{nc} and p^c be the unique maximizers of (1) and (2) respectively. It is optimal for agent A (not) to share information if the value of (1) at p^{nc} is (greater) less than the value of (2) at p^c. Thus, in any given situation the set of optimal strategies of agent A can consist of at most two elements: (p^c, agree to share information) and (p^{nc}, refuse to share information). Let δ denote the probability with which agent A chooses the first of these strategies. Clearly, $\delta = F_A(p^{nc})$.

Then our findings can be summarized in the following lemma:

Lemma 1 *Suppose that agent B is expected to follow some strategy $(F_B(q), \sigma(q))$ and agent A accepts the incentive scheme offered to her by the firm. Then agent A's optimal strategy can be represented as a triple $(p^c, p^{nc}, \delta) \in [0,1]^3$ s.t. p^{nc} (p^c) maximizes (1) ((2)), while $\delta \in [0,1]$ is such that $\delta = 1$ ($\delta = 0$) if (1) evaluated at p^{nc} is greater (less) than (2) evaluated at p^c.*

The optimal strategy of the agent B can be characterized in the same way. We will denote it by (q^c, q^{nc}, σ). As before, let $\bar{q} \equiv \bar{q}^c\bar{\sigma} + \bar{q}^{nc}(1-\bar{\sigma})$.

Given the strategy combination (p^c, p^{nc}, δ) and (q^c, q^{nc}, σ), the expected profit of the firm A is given by the following:

$$\begin{aligned}
&W^A(v_{21}, v_{22}, v_{12}, v_{11}, p^c, p^{nc}, \delta, q^c, q^{nc}, \sigma) \\
&= (1-\delta)[(\pi_{21} - h(v_{21}))p^{nc}(1-\bar{q}) + (\pi_{22} - h(v_{22}))p^{nc}\bar{q} \\
&+ (\pi_{12} - h(v_{12}))(1-p^{nc})\bar{q} + (\pi_{11} - h(v_{11}))(1-p^{nc})(1-\bar{q}) \\
&+ \delta(1-\bar{\sigma})[(\pi_{21} - h(v_{21}))p^c(1-q^{nc}) + (\pi_{22} - h(v_{22}))p^c q^{nc} \\
&+ (\pi_{12} - h(v_{12}))(1-p^c)q^{nc} + (\pi_{11} - h(v_{11}))(1-p^c)(1-q^{nc})] \\
&+ \delta\bar{\sigma}[(\pi_{22} - h(v_{22}))(1-(1-p^c)(1-q^c)) + (\pi_{11} - h(v_{11}))(1-p^c)(1-q^c)]
\end{aligned} \tag{3}$$

The expression for the expected payoff of the firm B is similar. In equilibrium, each firm choose an incentive scheme which maximizes its expected payoff under its beliefs about the other agent's strategy and given the optimal response of its own agent to the incentive scheme. Possible information sharing between the agents implies that an agent's optimal response to the incentive scheme depends also on her beliefs about the other agent's strategy. This feature of the environment generates an interaction between the incentive schemes and makes computing and characterizing the equilibria in this game quite complicated.

Since agent j cannot observe the incentive scheme offered to the agent i ($i, j \in \{A, B\}$), firm i cannot change agent j's beliefs about agent i's strategy by making an unexpected deviation from its equilibrium strategy. This unobservability assumption, which can be justified by the possibility of secret renegotiation between a firm and its agent, eliminates any signaling element in the firm's offer of an incentive scheme. Therefore, if the firm i would like to induce its agent to follow the strategy (p^c, p^{nc}, δ) under some beliefs about agent j's strategy, it is optimal for the firm i to choose such an incentive scheme which induces this behavior of agent i at the minimal expected cost. If the original incentive scheme does not minimize this cost, then the firm i can do better by offering a different incentive scheme which induces the same behavior of agent i. Such a deviation is not observed by the agent j and therefore cannot change its strategy. Therefore, under given beliefs about agent j's strategy, firm i's problem can be broken into two parts: [1]

- Minimization: For any action of agent i, compute an incentive scheme which induces this action at the minimal cost.
- Maximization: Maximize the expected profits and compute which action it is optimal to induce.

Suppose that the firm i offers an incentive scheme $\mathcal{I} = \{v_{21}, v_{22}, v_{12}, v_{11}\}$ s.t. the agent i finds it optimal to randomize with probability $\delta \in (0, 1)$ between actions (p^c, agree to share information) and (p^{nc}, refuse to share information). In this case, both the firm and the agent are indifferent between these two actions. If the firm gets a strictly higher payoff following the agent's action (p^{nc}, refuse to share information) ((p^c, agree to share information)) then from inspection of (1) and (2) it follows that it can obtain a strictly higher payoff by increasing v_{21} (v_{22}) by any $\epsilon > 0$.

Therefore, we can replace agent's randomization with the firm's randomization in the following way. Let $\mathcal{I}'$ and $\mathcal{I}''$ be two identical copies of the incentive scheme $\mathcal{I}$. Suppose that the agent i chooses action (p^c, agree to share information) when offered $\mathcal{I}'$, and chooses action (p^{nc}, refuse to share information) if offered $\mathcal{I}''$. Both responses are optimal for the agent, and the firm is indifferent between offering $\mathcal{I}'$ or $\mathcal{I}''$. Let the firm i offer $\mathcal{I}'$ with probability δ and $\mathcal{I}''$ with probability $(1-\delta)$. The resulting distribution of agent's strategies and payoffs are identical to the ones which are induced when the firm offers the incentive scheme $\mathcal{I}$ and the agent randomizes.

This argument allows us, without loss of generality, to restrict the analysis to two classes of incentive schemes:

- **type *NC*, collusion-proof:** incentive schemes from this class induce the agent to refuse to share information with probability 1.
- **type *CC*, collusive incentive schemes:** incentive schemes of this class induce the agent to agree to share information with probability 1.

As established above, optimal incentive schemes must be cost-minimizing. Therefore, an incentive scheme of type NC minimizes the firm's expected cost of inducing desired effort p^{nc} and providing incentives for the agent not to share information. An incentive scheme of type CC minimizes the expected cost of inducing the desired effort p^c and providing the agent with incentives to share information. These findings are summarized in the following lemma:

Lemma 2 *Without loss of generality, the incentive schemes which can be optimal for a firm to offer belong to one of the two classes: NC and CC. Incentive schemes in the class NC minimize the firm's expected cost of inducing the agent to take a particular effort and refuse to share information. Incentive schemes in the class CC minimize the cost of inducing the agent to take a particular effort and agree to share information.*

[1] This method is due to Grossman & Hart [10].

3 Optimal incentive schemes

At first, we characterize the incentive schemes in the class *NC*. Assuming that the agent B is expected to follow the strategy (q^c, q^{nc}, σ), we consider which incentive scheme the firm A should offer if wants its agent to exert effort p and refuse to share information. This incentive scheme is denoted by $NC(p, (q^c, q^{nc}, \sigma))$ and is characterized in the following lemma.

Lemma 3 *Suppose that agent B is expected to play the strategy (q^c, q^{nc}, σ), and the firm A wants to induce its agent to take effort p and refuse to share information. Then there is a unique optimal incentive scheme for agent A $NC(p, (q^c, q^{nc}, \sigma))$ with the following ordering of the rewards: $v_{21} > v_{22} > v_{12} > v_{11}$.*

Proof: see Appendix.

It is easy to see that if the rewards offered to an agent depend only on the quality of her product, i.e. $v_{21} = v_{22} > v_{12} = v_{11}$, then this agent will be willing to participate in the information sharing, because it gives her a chance to improve the quality of her product. Hence, the rewards in the incentive scheme of class *NC* have to depend on the quality of the products designed by both agents. Specifically, the firm penalizes its agent for delivering the product of the same quality as the one delivered by the other agent. However, even in the absence of information sharing the agents will deliver products of the same quality with a positive probability. Therefore, not to discourage effort, the penalty in the state (θ_2, θ_2) cannot be too large. This explains why it is optimal to set $v_{22} > v_{12}$. Perhaps the ordering $v_{12} < v_{11}$ may not appear intuitive. However, when vertical differentiation increases firms' profits, it will be the case that $\pi_{12} > \pi_{11}$. Then the firms can support the ordering $v_{12} < v_{11}$ by instituting a profit-sharing scheme.

Lemma 3 implies that preventing information exchange requires the use of peer comparison in the structure of compensation. Thus we provide a new explanation for the use of peer-comparison. Here it arises in an environment where there are neither correlated productivity shocks, nor correlated private information, which, as shown in the literature, make the peer comparison optimal.

Preventing information exchange is costly, since the firm will have to compensate a risk-averse agent for the additional variability of the rewards. In the next sections we will establish whether and when doing this is optimal for the firm. Here we can point out two types of negative effects of information exchange for the firm. The first is spillover of innovations to the other firm, which can make it impossible to achieve technological leadership in the industry. The second is agent's lower effort as a result of free-riding. In the proof of lemma 3 it is shown that under a fixed incentive scheme an agent would take a lower effort if she decides to take part in the information sharing and expects the other agent to do so with a positive probability. In this case, with some probability the agent obtains a high quality design from the other agent, which means that she needs to work less hard.

This implies that inducing effort may actually be costlier for the firm in the situation when the agents exchange information, despite the fact that the firm has to employ expensive peer comparison to prevent information sharing. As we are going to see later, even if a firm's profits are not decreased substantially when the other firm produces the product of the same quality, it will still be optimal to prevent information sharing in order to eliminate free-riding and preserve the agent's incentives to exert effort.

As the next step, we will characterize the incentive schemes of class CC. Assuming that the agent B is expected to follow the strategy (q^c, q^{nc}, σ), let $CC(p^c, (q^c, q^{nc}, \sigma))$ denote the optimal incentive scheme which induces agent A to follows the strategy (p^c, agree to share information). This incentive scheme is characterized in the following lemma.

Lemma 4 *Suppose that agent B is expected to use the strategy $(q^c, q^{nc}, \sigma))$, and the firm A wants to induce its agent to exert effort p and agree to share information. Then there is a unique optimal incentive scheme $CC(p, (q^c, q^{nc}, \sigma))$ which the firm A should offer. In this incentive scheme the rewards are ordered in the following way: $v_{21} \geq v_{22} > v_{11} \geq v_{12}$ (non-strict inequalities hold as equalities if $q^c = 0$, i.e. if agent B is not expected to share information.)*

One may wonder why it is not necessarily optimal to set $v_{21} = v_{22}$ and $v_{12} = v_{11}$ in an incentive scheme of type CC. When offered such an incentive scheme, the agent will certainly agree to share information. Yet, it may not be the cost minimizing way to induce effort. When the other agent is expected to share information with probability 1, then the rewards v_{21} and v_{12} are irrelevant for effort elicitation. But when there is a non-zero probability that the other agent will not share information, then increasing v_{21} generates more powerful incentives at a lower cost than increasing v_{22}.

The incentive effect on effort of raising reward v_{22} is diluted because of free-riding. The information exchange occurs with positive probability, and therefore agent A may get a higher payoff v_{22} even if she fails to discover a high quality design, but agent B does discover it. On the other hand, the agent A can rely only on her own effort if she wants to increase her chances of obtaining a high payoff v_{21}. To illustrate this formally, consider the ratio $R(v_{21})$ ($R(v_{22})$) of the coefficients on v_{21} (v_{22}) in the firm's cost function and in the agent's incentive constraint. This ratio can be regarded as a measure of the cost of providing incentives to exert effort via the corresponding element of the incentive scheme. We obtain:

$$R(v_{21}) = p < R(v_{22}) = p + \frac{\sigma q^c}{\sigma(1-q^c) + (1-\sigma)q^{nc}}$$

But increasing v_{21} may cause agent's payoff under no information exchange to exceed that under information exchange. To avoid this and make the information sharing more attractive, the firm will have to set v_{12} below v_{11}.

It is optimal to set $v_{21} = v_{22} > v_{11} = v_{12}$ in the two boundary cases when the agent B either always refuses to share information ($\sigma = 0$) or always agrees to do so ($\sigma = 1$). The optimal CC incentive schemes coincide, but the underlying reasons are distinct. In the first case ($\sigma = 1$), as already noted, the rewards v_{21} and v_{12} are never paid out, and so the firm cannot do anything to prevent free-riding. In the second case ($\sigma = 0$), the agent A cannot free-ride and therefore it is optimal to offer the incentive scheme with the lowest variability, i.e. agent A's rewards do not depend on the quality of agent B's product.

Obviously, this characterization also applies to the incentive schemes optimal for the firm B. The optimal incentive schemes define the firms' cost functions. Accordingly, let $G^{nc}(p|q^c, q_{nc}, \sigma)$ $(G^{cc}(p|q^c, q_{nc}, \sigma))$ denote the value of the objective function in the Problem $NC(p, (q^c, q_{nc}, \sigma)$ $(CC(p, q^c, q_{nc}, \sigma))$ which shows the firm's cost of inducing the agent to take effort p and refuse (agree) to share information when the other agent is expected to follow the strategy (q^c, q_{nc}, σ). These cost functions are characterized in the following lemma.

Lemma 5 *The cost function $G^{cc}(p|q^c, q_{nc}, \sigma)$ is continuous in all of its arguments and increasing in p. The cost function $G^{nc}(p|q^c, q_{nc}, \sigma)$ is increasing in p and continuous in all arguments almost everywhere except at $\sigma = 0$.*

Proof: See appendix.

The discontinuity of the cost function at $\sigma = 0$ may complicate the analysis of equilibria in this model. However, this specific discontinuity turns out to be harmless, because it happens at the irrelevant point of the parameter space, as established in the following lemma:

Lemma 6 $\exists \underline{\sigma} > 0$ *s.t. if the agent B agrees to share information with probability $\sigma \leq \underline{\sigma} > 0$, then the firm A will offer only incentive schemes of class CC, i.e. it will not prevent its agent from sharing information.*

Proof: See appendix.

The intuition behind this lemma is easy to understand. When the agent B agrees to exchange information with a very low probability, allowing agent A to share information will not affect her effort significantly, as the probability of information exchange remains small anyways. Then the firm A will not be willing to incur an extra cost of preventing the information exchange.

The cost functions are not necessarily convex in p, which makes the task of characterizing equilibria more complex. Equilibria may only exist in mixed strategies when firms randomize between incentive schemes. For example, if $G^{nc}(p, .)$ is not globally convex in p, then it is possible that the firm A obtains maximum profits by offering either $NC(p_1, .)$ or $NC(p_2, .)$ for some $p_1, p_2 \in [0, 1]$. If the firm randomizes between these incentive schemes with probability $t \in (0, 1)$, then the expected effort is given by $\hat{p} = tp_1 + (1-t)p_2$. Notice that the payoffs of the firm B and agent B depend only on $\hat{p}$, and are unaffected by whether the firm A uses a random strategy with expected effort $\hat{p}$ or a pure strategy inducing $\hat{p}$. Notice that the randomization described here is between incentive schemes of the same type NC or CC.

Accordingly, define the expected cost function $\tilde{G}^{nc}(p, .)$ to be the convex hull of the effort cost function $G^{nc}(p, .)$ (see figure 1): $\tilde{G}^{nc}(p|.) = \text{conv} G^{nc}(p|.)$ (see Rockafeller ([21]). By Theorem 2.3 in [21]:

$$\tilde{G}^{nc}(p|.) = \min_{p_1, p_2 :\, tp_1 + (1-t)p_2 = p} tG^{nc}(p_1|.) + (1-t)G^{nc}(p_2|.) \tag{4}$$

Similarly, the expected cost function $\tilde{G}^{CC}(p|.)$ is defined to be the convex hull of the function $G^{CC}(p|.)$. The functions $\tilde{G}^{nc}(p|.)$ and $\tilde{G}^{c}(p|.)$ show the true cost incurred by the firm when it induces its agent to exert expected effort p and, respectively, refuse or agree to share the information. It is easy to see that both $\tilde{G}^{nc}(p|.)$ and $\tilde{G}^{c}(p|.)$ are increasing and continuous and weakly convex in p. The latter property means that the functions are linear on the intervals where they do not coincide with the cost functions $G^{nc}(p|.)$ and $G^{CC}(p|.)$ respectively.

Next, let $V^{nc}(p|q^c, q^{nc}, \sigma)$ $(V^c(p|q^c, q^{nc}, \sigma)))$ denote the firm's expected profit when the agent's expected effort is p and she refuses (agree) to share information under standard assumptions about agent B's strategy. Obviously,

$$\begin{aligned} V^{nc}(p|q^c, q^{nc}, \sigma) \equiv & \\ & \pi_{21}p(1-\bar{q}) + \pi_{22}p\bar{q} + \pi_{12}(1-p)\bar{q} + \pi_{11}(1-p)(1-\bar{q}) \\ & - \tilde{G}^{nc}(p|q^c, q^{nc}, \sigma) \qquad (5) \\ V^c(p|\sigma, q^c, q^{nc})) \equiv & \\ & (1-\sigma)[\pi_{21}p(1-q^{nc}) + \pi_{22}p\bar{q}^{nc} + \pi_{12}(1-p^c)\bar{q}^{nc} + \pi_{11}(1-p^c)(1-\bar{q}^{nc})] \\ & + \bar{\sigma}\,[\pi_{22}(1-(1-\bar{q}^c)(1-p^c)) + \pi_{11}(1-p^c)(1-\bar{q}^c)] \\ & - \tilde{G}^c(p^c, \bar{\sigma}, \bar{q}^c, \bar{q}^{nc}) \qquad (6) \end{aligned}$$

It is easy to see that $V^{nc}(p|.)$ $(V^c(p|.))$ is (weakly) concave, and therefore has a convex set of maximizers. In other words, when the firm induces its agent to refuse (agree) to exchange information, there is either a unique optimal effort p^{nc*} (p^{c*}), or the set of optimal efforts constitutes a closed interval.

When p^{nc*} (p^{c*}) is unique, $V^{nc}(p|.)$ $(V^c(p|.))$ is strictly concave in the neighborhood of p^* and $\tilde{G}^{nc}(p|.)$ $(\tilde{G}^c(p|.))$ is strictly convex (both can have a kink at this point). To elicit p^{nc*} (p^{c*}), the firm uses the incentive scheme $NC(p^*|.)$ $(CC(p^*|.))$ and does not randomize.

If the set of maximizers of $V^{nc}(p|.)$ $(V^c(p|.))$ is some interval $[p_L^{nc*}, p_H^{nc*}]$ $([p_L^{c*}, p_H^{c*}])$, then $V^{nc}(p|.)$ $(V^c(p|.))$ is constant on this interval, which implies that $\tilde{G}^{nc}(p|.)$ $(\tilde{G}^c(p|.))$ is linear on this interval and correspondingly:

$$\frac{d\tilde{G}^{nc}(p|.)}{dp} = (\pi_{21} - \pi_{11})(1-\bar{q}) + (\pi_{22} - \pi_{12})\bar{q}$$

$$\frac{d\tilde{G}^{c}(p|.)}{dp} = (1-\sigma)\left((\pi_{21} - \pi_{11})(1-q^{nc}) + (\pi_{22} - \pi_{12})q^{nc}\right) + \sigma\left((v_{22} - v_{11})(1-q^c)\right)$$

It is easy to see that the boundary points of the interval $[p_L^{nc*}, p_H^{nc*}]$ $([p_L^{c*}, p_H^{c*}])$ correspond to the firm's pure strategies, i.e. it offers incentive schemes $NC(p_L^{nc*}|.)$ $(CC(p_L^{c*}|.))$ and $NC(p_H^{nc*}|.)$ $(CC(p_H^{c*}|.))$. Any effort $p \in (p_L^{nc*}, p_H^{nc*})$ $(p \in (p_L^{c*}, p_H^{c*}))$ will be induced only in expectation when the firm randomizes between $NC(p_L^{nc*}|.)$ $(CC(p_L^{c*}|.))$ and $NC(p_H^{nc*}|.)$ $(CC(p_H^{c*}|.))$ with probability $t \in (0,1)$ such that $p = tp_L^{nc*} + (1-t)p_H^{nc*})$ $(p = tp_L^{c*} + (1-t)p_H^{c*})$.

Thus, the set of the firm's optimal strategies in this case includes two pure strategies $NC(p_L^{nc*}|.)$ and $NC(p_H^{nc*}|.)$ $(CC(p_L^{c*}|.)$ and $CC(p_H^{c*}|.))$ and a continuum of mixed strategies representing randomization between these two incentive schemes. We can summarize this in the following lemma:

Lemma 7 *Suppose that the firm A wants to induce its agent to agree (refuse) to share information. Then the set of optimal incentive schemes includes either a unique incentive scheme or two incentive schemes. Thus, a firm's optimal strategy can put positive probability on at most four incentive schemes: two of type NC and two of type CC.*

4 Equilibria

Existence of an equilibrium is a non-trivial question. An agent's optimal strategy depends not only on the incentive scheme offered by her employer, but also on her beliefs about the strategy of the other firm's agent and, consequently, the other firm's incentive scheme. Thus, when choosing its incentive scheme, a firm has to play the 'best response' to the incentive scheme(s) offered by the other firm. To prove the existence of an equilibrium in this situation, we will use the appropriate version of the revelation principle.

Consider a modified game M in which firms A and B simultaneously choose strategies $(p^c, p^{nc}, \delta) \in [0,1]^3$ and $(q^c, q^{nc}, \sigma) \in [0,1]^3$ respectively, and firm A's payoff is equal to:

$$W_A((p^c, p^{nc}, \delta), (q^c, q^{nc}, \sigma)) \equiv (1-\delta)V^{nc}(p^{nc}|q^c, q^{nc}, \sigma) + \delta V^c(p^c|q^c, q^{nc}, \sigma) \tag{7}$$

and firm B's payoff is equal to:

$$W_B((q^c, q^{nc}, \sigma), (p^c, p^{nc}, \delta)) \equiv (1-\sigma)V^{nc}(q^{nc}|p^c, p^{nc}, \delta) + \sigma V^c(q^c|p^c, p^{nc}, \delta) \tag{8}$$

Lemmas 2, 3 and 7 imply that the set of equilibrium strategies in the game M is equivalent to the set of the agents' equilibrium strategies in the original game. Then, after solving the game M, we can compute the equilibrium incentive schemes by 'inverting' the cost functions $\tilde{G(.)}^{nc}$ and $\tilde{G(.)}^{c}$.

Firms A's payoff $W_A(.)$ is additively separable in p^{nc} and p^c, while $W_B(.)$ is additively separable in q^{nc} and q^c. Then the optimal efforts p^{nc} (q^{nc}) and p^c (q^c) are determined independently of each other. Therefore, firm A's best response to the firm B's strategy can be determined as follows: find the sets of maximizers of $V^{nc}(p|q^c, q^{nc}, \sigma)$ and $V^c(p|q^c, q^{nc}, \sigma)$ respectively. By lemma 7, these sets of maximizers are convex. Then choose δ optimally depending on whether $V^{nc}(p^{nc*}|q^c, q^{nc}, \sigma)$ is greater or less that $V^c(p^{c*}|q^c, q^{nc}, \sigma)$ where p^{nc*} and p^{c*} are elements of the corresponding sets of maximizers. The set of optimal δ^* can be either 0, or 1, or $[0,1]$. Thus, the set of the firm A's best responses to any strategy of the firm B is convex. Obviously, the same is true for the set of the firm B's best responses.

By lemmas (3) and (4), $W_A(.)$ and $W_B(.)$ are continuous everywhere except at $\sigma = 0$. To deal with this problem, we further modify the game M and define the game M^* where, instead of (7) and (8), the payoffs are given by the following functions which are everywhere continuous :

$$(1-\delta)\max\{V^{nc}(p^{nc}|q^c, q^{nc}, \sigma), V^c(p^c|q^c, q^{nc}, \sigma) - \Delta\} + \delta V^c(p^c|q^c, q^{nc}, \sigma) \tag{9}$$

$$(1-\sigma)\max\{V^{nc}(q^{nc}|p^c p^{nc}, \delta), V^c(q^c|p^c, p^{nc}, \delta) - \Delta\} + \sigma V^c(q^c|p^c, p^{nc}, \delta) \tag{10}$$

where $\Delta = \frac{1}{2}\left(V^c(p^c|q^c, q^{nc}, 0) - V^{nc}(p^{nc}|q^c, q^{nc}, 0)\right) > 0$. By lemma (5), the firms' best responses in the games M and M^* are the same, and the values of the profit functions at the optimum are also the same. Then by Berge's Maximum theorem, the best response correspondences $(p^{nc}, p^c, \delta) \longrightarrow (q^{nc}, q^c, \sigma)$ and $(q^{nc}, q^c, \sigma) \longrightarrow (p^{nc}, p^c, \delta)$ derived by maximizing (9) and (10) respectively are upper hemi-continuous. By the Kakutani's fixed point theorem, there exists an equilibrium $(p^{NC*}, p^{C*}, \delta^*, q^{NC*}, q^{C*}, \sigma^*)$ in the game M^*, and hence, an identical equilibrium in the game M.

To see that equilibria in the game M correspond to equilibria in the original game where the two firms offer incentive schemes to their agents, note that if the firm A expects agent B to take the action $(q^{NC*}, q^{C*}, \sigma^*)$, then its best response is to induce her agent to take the action $(p^{NC*}, p^{C*}, \delta^*)$, and vice versa. The corresponding incentive schemes exist and are uniquely determined as shown in lemmas (2),(3), (4) and (7).

Having established the existence of equilibria, our next task is to characterize them, and demonstrate how the nature of the interaction between the firms in the product market and the configuration of the payoffs determine whether the information exchange between the employees does or does not occur, i.e. whether the firms offer incentive schemes of type CC or NC.

We can identify several factors which affect this choice. First of all, if the payoff to technological leadership is sufficiently large (i.e. π_{21} is significantly greater than all other payoffs), then preventing exchange of information is essential for achieving high profitability.

Secondly, preventing the information exchange allows to eliminate free-riding by the employees. When an agent gains access to the results of the R&D performed by the other agent through the information exchange, her incentives to exert effort are diminished. Thus, the firm's effective cost of effort goes up, as it has to offer more high-powered incentive schemes.

On the other hand, preventing information exchange is costly for the firm. It requires using peer comparison, which introduces additional variance in the the structure of compensation. Since an agent is risk-averse, she has to be compensated for bearing this additional variance.

Moreover, a firm may have a strategic interest in fostering the information exchange, because through it the firm can gain access to the results of the R&D performed in other firms.

Another factor which makes 'collusive' incentive schemes CC more attractive is the firm's own incentive to free-ride. For the information exchange to be prevented, only one of the firms needs to induce its agent not to participate in it. The other firm can save the cost of doing this. This free-riding effect is at the core of the result in lemma 6, and it also leads to the asymmetry of pure-strategy equilibria established below. Since each firm wants to be the free-rider, which may lead to the lack of coordination in a mixed strategy equilibrium.

Naturally, each of these factors can be more or less significant depending on the structure of payoffs determined by the nature of the competition in the product market. Specifically, the firms may be involved in the race for technological leadership, or they may be operating in separate markets (separate regions), so that the payoff earned by one firm does not depend on the quality of the product supplied by the other. Similarly, the spillover effect may be weak or strong.

To understand what happens under these and other possible regimes, we will allow the vector of payoffs $(\pi_{22}, \pi_{21}, \pi_{12}, \pi_{11})$ to vary, and characterize equilibria in a number of special, yet quite common and intuitive cases.

1. Technological leadership is valuable: $\pi_{21} - \pi_{22} > \pi_{22} - \pi_{12}$.
Information exchange is prevented with positive probability.

Suppose that only incentive schemes of class CC are used in some equilibrium. Then information exchange occurs with probability 1. Let p^* be the highest effort taken with a positive probability in this equilibrium and, without loss of generality, assume that it is taken by the agent A. Let $\bar{q}$ denote agent B's expected effort. Obviously, $p^* \geq \bar{q}$. Because the information exchange occurs with probability 1, the optimal incentive scheme $\mathbf{v}$ which induces agent A to take p^* is such that: $(v_{22} - v_{11})(1 - \bar{q}) = D'(p_1^*)$, and v_{22} or v_{11} are the only rewards that are paid with positive probability.

Now, let the firm A offer the incentive scheme $\mathbf{w}$ s.t. $w_{21} = w_{22} = w_{12} = v_{22}$, $w_{11} = v_{11}$. Then it is optimal for the agent to take effort p^* and refuse to exchange information. To see this, notice the agent is indifferent between exchanging and not exchanging the information and her incentive compatibility condition under no information exchange is given by the following:

$$(w_{21} - w_{11})(1 - \bar{q}) + (w_{22} - w_{12})\bar{q} = (v_{22} - v_{11})(1 - \bar{q}) = D'(p^*)$$

Then the firm A's expected costs under the incentive schemes $\mathbf{v}$ and $\mathbf{w}$ are the same. However, using $\pi_{21} - \pi_{22} > \pi_{22} - \pi_{12}$, we find that the change in the expected benefit is positive and is equal to:

$$\pi_{21} p^*(1 - \bar{q}) + \pi_{12}(1 - p^*)\bar{q} - \pi_{22}[p^*(1 - \bar{q}) + (1 - p^*)\bar{q}] > 0 \tag{11}$$

2. High payoff to technological leadership: Information exchange is prevented.

To prove this result, we fix $\pi_{21} - \pi_{11}$, but otherwise let the payoffs vary. Then the following result is obtained:

Lemma 8 *$\exists k \geq 0$ s.t. if $\pi_{21} - \pi_{22} \geq k(\pi_{22} - \pi_{12})$, then there exists an equilibrium in which one of the agents refuses to exchange information with probability 1, while the other agent agrees to exchange information with probability 1.*

Proof: See appendix.

When the benefit from winning the R&D race is sufficiently high, it becomes very costly to allow for the information exchange. Therefore in an equilibrium information exchange is prevented with probability 1. This implies that one of the firms uses only incentive schemes of the class NC, which make the reward contingent on the qualities of the products developed by both firms. This allows the other firm to free-ride and save the cost of preventing the information exchange. This firm offers only incentive schemes of type CC, and rewards its employee only on the basis of her performance. Thus, the compensation schemes may very significantly across firms. This result provides as an explanation for the observed variety of the compensation packages offered in the same industry.

Although this equilibrium may not be unique, it has the attractive property that none of the firms randomize between incentive schemes of different types, which can can serve as justification for selecting it. In the framework of this model we are unable to predict, which firm will prevent information exchange and which firm will free-ride. However, the result suggests that there is an advantage of being the first and acting as a Stackelberge leader. Accordingly, we may observe that the first entrant into the market offers incentive scheme which only reward the engineers for the high quality of their products, whereas later entrants also offer incentive stock options.

3. Easy imitation of innovations: No information exchange.

Suppose that an innovation developed by one firm can be immediately copied or re-engineered by another firm. In this case, the payoffs have the following structure: $\pi_{21} = \pi_{22} = \pi_{12} > \pi_{11}$. Then the result follows from lemma 8.

The intuition is particularly easy to understand. Whatever an employee can learn about the other firm's innovation through direct information exchange, the firm can itself learn and quickly imitate, once the other firm brings the innovation to the market. Thus, the information exchange brings no benefit for either firm. However, as demonstrated in the proof of lemma 8, preventing the information exchange allows a firm to reduce the cost of effort by eliminating employee free-riding. Of course, when one firm prevents its agent from exchanging information, the other firm free-rides and saves the cost of doing this.

4. Firms serve different markets: Information exchange takes place.

In this case a firm's payoff depends only on the quality of the product delivered by its agent, and not on the quality of the other firm's product, i.e. $\pi_{21} = \pi_{22} > \pi_{12} = \pi_{11}$. It is easy to see that each firm would like to encourage information exchange between the employees, if it does not lead to excessive free-riding by the employees. In this situation, the firms would view the information exchange as cooperation between employees, whereas in the situations considered earlier they would probably view it as collusion between the employees against the firms.

Let us show that this is true for certain effort cost functions. Suppose that the probability of the information exchange is equal to 1, the firm A uses the incentive scheme (v_H, v_L) to induce its agent to take effort p, and the agent B takes effort q. Then the agent A's incentive compatibility condition is:

$$(v_H - v_L)(1 - q) = D'(p)$$

It follows that the firm A ends up with the high quality product with probability
$1 - (1 - p)(1 - q)$. Now consider effort p' satisfying

$$(v_H - v_L) = D'(p')$$

Note that $p' \geq p$. Clearly, the firm A's expected cost of preventing the information exchange and inducing its agent to take the effort p' is greater than $h(v_{22})p^{nc}+h(v_{11})(1-p^{nc})$ because of the additional cost of preventing information exchange. Then allowing the information exchange to take place is better for the firm if $1-(1-p)(1-q) \geq p'$, or, equivalently $\frac{D'(p')}{D'(p)} \geq \frac{1-p'}{1-p}$. The cost functions which satisfy this condition (as well as all the other assumptions) include $D(p) = -\log(1-p)$. or $D(p) = -\frac{1}{(1-p)^n}$ where $n > 0$.

This condition ensures that the marginal cost of effort increases fast enough, so that the employee does not reduce her effort by too much under information exchange, i.e. the degree of free-riding is not too large.

5. Differentiated Bertrand competition: Employee compensation is a sum of a bonus and a quality premium.

If the firms compete by setting prices in the market where consumers differ in their willingness to pay for the quality, then the profits are zero if firms offer products of the same quality (high or low). However, when the two firms offer products of different quality, then both firms earn some profits. The firm offering the lower quality captures the lower end of the market and earns some profits, as is the case with many hi-tech and computer products. Then the firms' payoffs are ordered in the following way:

$$\pi_{21} > \pi_{12} > \pi_{22} = \pi_{11} = 0$$

Note that the other assumptions in the paper guarantee that each firms wants to be the producer of the high-quality product, and there is noe equilibrium in which one firm always produces a low-quality product. Since the assumption of the case 2 is satisfied, there exists an equilibrium in which one of the firms prevents the information exchange with probability 1, and the other does not. By lemma 3, the incentive scheme offered by the first firm has the following structure: $v_{21} > v_{22} > v_{12} > v_{11}$. It is easy to interpret this payoff structure as follows:

Payment to Agent = Quality Premium + Profit Share

The agent's base pay is v_{11}. The premium for high quality is $v_{22} - v_{11}$. Profit shares are $v_{21} - v_{22}$ if the state of the world is (θ_2, θ_1), and $v_{12} - v_{11}$ if state of the world is (θ_1, θ_2). In the states where firms deliver products of the same quality, firms get no profits and agents' profit shares are equal to zero as well.

One method to introduce profit sharing in the structure of compensation is to give stock options to the employees. Since the value of the stock increases in the firm's profits, it will generate the desired incentive effect, and prevent an employee who is granted the stock option from sharing her technical information with the employee working for the other firm.

In contrast to the standard explanations, bonuses and stock options are used here primarily not to elicit effort and enhance productivity, but to prevent information exchange or collusion between researchers. From this standpoint, the proliferation of the stock options as a form of compensation in the Silicon Valley and the computer industry in general could be explained by the need of the firms to prevent excessive spillover of information in the closely-knit community of programmers and engineers.

On the other hand, our results imply that the firms that do not use stock options or other forms of profit sharing, may be doing so either to decrease their compensation costs, or to foster exchange of information and cooperation between their employees and the employees of the other firms.

5 Concluding remarks

In the existing literature on the R&D a firm is normally viewed as a 'black box', and issues of its internal organization are left outside the scope of the analysis. This paper demonstrates some of the implications of relaxing this assumption.

Our central conclusion suggests that the use of bonuses and stock options as a form of compensation is more likely to be observed in the industries with high degree of communication between employees across firms.

The paper leaves open an important question of the overall welfare effect of the information exchange. By preventing unnecessary duplication of the research effort such exchange can potentially be welfare-improving. However, the positive effect is diminished due to the employees' free-riding which can cause the overall research effort to be insufficient. Moreover, when the information exchange is prevented, its possibility has only negative consequences, as additional variance is introduced in the structure of compensation of the risk-averse agents. There is no consensus regarding this issue in the empirical literature as well. Schrader [25] maintains that the information exchange has a positive overall effect on the firms' profitability and the magnitude of the R&D effort, while Rogers [22] claims that the negative effects outweigh the positive ones.

The other issues which deserve further study include the analysis of the research joint ventures as a venue for employees' information sharing. From this point of view, it would be interesting to consider the employers' incentives to enter such ventures, and their choice of employees to be assigned to such ventures. I intend to explore these issues in future research.

6 Appendix

Proof of Lemma 3:

Suppose that agent j is expected to follow the strategy (q^c, q^{nc}, σ).
Let $\bar{q} = \sigma q^c + (1-\sigma) q^{nc}$. By lemma (2), incentive scheme $NC(p, (q^c, q^{nc}, \sigma))$, solves the following optimization problem:

Problem NC($p, (q^c, q^{nc}, \sigma)$**)**

$$\min_{(v_{21}, v_{22}, v_{12}, v_{11})} p\bar{q}h(v_{22}) + p(1-\bar{q})h(v_{21}) + (1-p)\bar{q}h(v_{12}) + (1-p)(1-\bar{q})h(v_{11}) \tag{12}$$

subject to: the incentive constraint

$$p = \arg\max_{x\in[0,1]} x\bar{q}v_{22} + x(1-\bar{q})v_{21} + (1-x)\bar{q}v_{12} + (1-x)(1-\bar{q})v_{11} - D(x) \tag{13}$$

the individual rationality constraint:

$$p\bar{q}v_{22} + (1-p)\bar{q}v_{21} + (1-p)\bar{q}v_{12} + (1-p)(1-\bar{q})v_{11} - D(p) \geq \underline{u} \tag{14}$$

and the no-collusion constraint:
a) if $\sigma > 0$

$$\begin{aligned} &p\bar{q}v_{22} + p(1-\bar{q})v_{21} + (1-p)\bar{q}v_{12} + (1-p)(1-\bar{q})v_{11} - D(p) \geq \\ &\max_{y\in[0,1]} \bar{\sigma}[v_{22}(1-(1-y)(1-\bar{q}^c) + v_{11}(1-y)(1-\bar{q}^c)] \\ &+ (1-\bar{\sigma})\,[y\bar{q}^{nc}v_{22} + y(1-\bar{q}^{nc})v_{21} + (1-y)\bar{q}^{nc}v_{12} + (1-y)(1-\bar{q}^{nc})v_{11}] - D(y) \end{aligned} \tag{15}$$

b) if $\sigma = 0$

$$p(1-\bar{q})v_{21} + (1-p)\bar{q}v_{12} \geq (p(1-\bar{q}) + (1-p)\bar{q})\, v_{22} \tag{16}$$

Among the above constraints, the no-collusion constraints are non-standard. They guarantee that it is not more profitable for the agent to agree to share information. Note that if the agent decides to share information, she will choose a different effort. Hence the maximization on the right-hand side of (15).

The no-collusion constraint (16) prevents the agent from choosing the weakly dominated strategy of refusing to share information if she expects the other agent to refuse. It requires the agent's payoff from refusing to share information to be (weakly) greater than the payoff which she gets by agreeing to collude, if there is a small probability that the other agent will 'tremble' and agree to exchange information. Imposing (16) eliminates implausible equilibria in which each agent refuses to share information only because she expects the other agent to do so, but each agent would agree to exchange information if there was a small positive probability that the other agent would do so.

Technically, (16) is necessary if we assume small trembles in the agent's agreement/refusal strategy. Consider a sequence of small trembles ϵ_n converging to 0. If $\sigma > 0$, then the trembles are 'too small' compared to σ. However, when $\sigma = 0$, then small trembles make the condition (16) necessary.

We solve the problem in the case $\bar{\sigma} > 0$. For $\sigma = 0$ the solution is similar. First of all, let's show that the minimization problem is convex in the incentive scheme. The objective is convex because it is additively separable in the agent's payoffs and the function $h(.)$ is convex. The individual rationality constraint (14) is linear in agent's rewards. Since the agent's expected utility function is strictly concave in p, the incentive constraint (13) can be replaced by the following first-order conditions which is also linear in agent's payoffs and is therefore convex in the incentive schemes:

$$(v_{21} - v_{11})(1-\bar{q}) + (v_{22} - v_{12})\bar{q} = D'(p) \tag{17}$$

To see that the NC constraint in (15) is convex, denote $\mathcal{I} \equiv (v_{21}, v_{22}, v_{12}, v_{11})$. Then (15) can be rewritten as:

$$K_1(\mathcal{I})p + C_1(\mathcal{I}) - D(p) \geq \max_z K_2(\mathcal{I})z + C_2(\mathcal{I}) - D(z) \tag{18}$$

where $K_1(.)$, $K_2(.)$, $C_1(.)$, $C_2(.)$ are linear functions defined on R^4. Choose two incentive schemes $\mathcal{I}'$ and $\mathcal{I}''$ that satisfy (18). Then we have:

$$\begin{aligned}
&K_1(t\mathcal{I}' + (1-t)\mathcal{I}'')p + C_1(t\mathcal{I}' + (1-t)\mathcal{I}'') - D(p) = \\
&t(K_1(\mathcal{I}')p + C_1(\mathcal{I}') - D(p)) + (1-t)(K_1(\mathcal{I}'')p + C_1(\mathcal{I}'') - D(p)) \geq \\
&t\max_z\{K_2(\mathcal{I}')z + C_2(\mathcal{I}') - D(z)\} + (1-t)\max_z\{K_2(\mathcal{I}'')z + C_2(\mathcal{I}'') - D(z)\} \geq \\
&t(K_2(\mathcal{I}')r + C_2(\mathcal{I}') - D(r)) + (1-t)(K_2(\mathcal{I}')r + C_2(\mathcal{I}') - D(r)) = \\
&K_2(t\mathcal{I}' + (1-t)\mathcal{I}'')p + C_2(t\mathcal{I}' + (1-t)\mathcal{I}'') - D(r)
\end{aligned} \tag{19}$$

Note that the last inequality is true for any $r \in [0,1]$. Therefore,

$$\begin{aligned}
&K_1(t\mathcal{I}' + (1-t)\mathcal{I}'')p + C_1(t\mathcal{I}' + (1-t)\mathcal{I}'') - D(p) \geq \\
&\max_z\{K_2(t\mathcal{I}' + (1-t)\mathcal{I}'')z + C_2(t\mathcal{I}' + (1-t)\mathcal{I}'') - D(z)\}
\end{aligned} \tag{20}$$

which proves the convexity of the NC constraint (15). Then let's write down the Lagrangian of the problem NC with multipliers $\lambda, \delta, \eta \geq 0$ and μ:

$$\begin{aligned}
&\mathcal{L}(v_{21}, v_{22}, v_{12}, v_{11}, \lambda, \delta, \eta; p, q^c, q^{nc}, \sigma) = \\
&p\bar{q}h(v_{22}) + p(1-\bar{q})h(v_{21}) + (1-p)\bar{q}h(v_{12}) + (1-p)(1-\bar{q})h(v_{11}) \\
&- \delta\left(\bar{q}(v_{22} - v_{12}) + (1-\bar{q})(v_{21} - v_{11}) - D'(p)\right) \\
&- \lambda\left(p\bar{q}v_{22} + p(1-\bar{q})v_{21} + (1-p)\bar{q}v_{12} + (1-p)(1-\bar{q})v_{11} - D(p) - \underline{u}\right) \\
&- \eta(p\bar{q}v_{22} + p(1-\bar{q})v_{21} + (1-p)\bar{q}v_{12} + (1-p)(1-\bar{q})v_{11} - D(p) \\
&- \max_y\{\sigma[v_{22}(1-(1-y)(1-q^c)) + v_{11}(1-y)(1-q^c)] + \\
&(1-\sigma)[yq^{nc}v_{22} + y(1-q^{nc})v_{21} + (1-y)q^{nc}v_{12} + (1-y)(1-q^{nc})v_{11}] - D(y))\}
\end{aligned} \tag{21}$$

Since the objective function is strictly convex, the solution to the Lagrangian minimization problem is unique. Let y^* be the unique maximizer of the expression on the right-hand side (15), i.e. y^* is the agent's optimal effort when she decides to exchange information. It is easy to show that $y^* < p$. Differentiating the Lagrangian with respect to the agent's rewards we obtain the following first-order conditions:

$$h'(v_{21}) = \lambda + \frac{\delta}{p} + \eta\left[1 - \frac{y^*(1-\bar{\sigma})(1-\bar{q}^{nc})}{p(1-\bar{q})}\right] \tag{22}$$

$$h'(v_{22}) = \lambda + \frac{\delta}{p} + \eta\left[1 - \frac{y^*\bar{q} + \bar{\sigma}\left(y^*(1-q^c) + (1-y^*)q^c\right)}{p\bar{q}}\right] \tag{23}$$

$$h'(v_{12}) = \lambda - \frac{\delta}{1-p^*} + \eta\left[1 - \frac{(1-y^*)(1-\bar{\sigma})\bar{q}^{nc}}{(1-p)\bar{q}}\right] \tag{24}$$

$$h'(v_{11}) = \lambda - \frac{\delta}{1-p^*} + \eta\left[1 - \frac{1-y^*}{1-p}\right] \tag{25}$$

Let's, at first, establish that $\eta > 0$, i.e. the no-collusion constraint (15) is binding. Suppose otherwise, i.e. $\eta = 0$. Then from (22)-(25) it follows that $v_{21} = v_{22} > v_{12} = v_{11}$. But then (15) fails. Contradiction.

Combining (22) and (23), we obtain

$$h'(v_{21}) - h'(v_{22}) = \eta \left(\frac{y^* \bar{q} + \sigma \left(y^*(1-q^c) + (1-y^*)q^c \right)}{p\bar{q}} - \frac{(1-\sigma)y^*(1-q^{nc})}{p(1-\bar{q})} \right) > 0$$

Hence, $v_{21} > v_{22}$. Consequently, $v_{12} < v_{22}$, because otherwise the no-collusion constraint (15) cannot be binding.

Finally, $v_{12} \geq v_{11}$ follows from (24) and (25) since $(1-\sigma)q^{nc} < \bar{q}$. Thus the desired ordering is established. Uniqueness follows by strict convexity of the objective function.

Finally, notice that the individual rationality constraint in (14) should also be binding, because otherwise all rewards can be reduced by some $\epsilon > 0$, which would not affect any other constraint, but would reduce the value of the objective function. **QED.**

Proof of Lemma (4)

By lemma 2, the incentive scheme $CC(p|q^c, q^{nc}, \sigma)$ can be derived by minimizing firm A's expected costs of inducing the agent to exert effort p and agree to exchange information when the agent B follows the strategy (q^c, q^{nc}, σ), i.e. by solving the following constraint minimization problem.

Problem CC$(p|q^c, q^{nc}, \sigma))$

$$\begin{aligned} &\min_{(u_{21},u_{22},u_{12},u_{11})} \sigma \left[h(u_{22})(1-(1-p)(1-q^c)) + h(u_{11})(1-p)(1-q^c) \right] \\ &+ (1-\sigma) \left[p(1-q^{nc})h(u_{21}) + pq^{nc}h(u_{22}) + (1-p)q^{nc}h(u_{12}) + (1-p)(1-q^{nc})h(u_{11}) \right] \end{aligned} \tag{26}$$

subject to the following individual rationality, incentive and collusion constraints:

$$\begin{aligned} &\sigma \left[u_{22}(1-(1-p)(1-q^c)) + u_{11}(1-p)(1-q^c) \right] \\ &+ (1-\sigma) \left[p(1-q^{nc})u_{21} + pq^{nc}u_{22} + (1-p)q^{nc}u_{12} + (1-p)(1-q^{nc})u_{11} \right] - D(p) \geq \underline{u} \end{aligned} \tag{27}$$

$$\begin{aligned} p = \arg\max_{x\in[0,1]} &\{ \sigma \left[u_{22}(1-(1-x)(1-q^c)) + u_{11}(1-x)(1-q^c) \right] \\ &+ (1-\sigma) \left[x(1-q^{nc})u_{21} + xq^{nc}u_{22} + (1-x)q^{nc}u_{12} + (1-x)(1-q^{nc})u_{11} \right] - D(x) \} \end{aligned} \tag{28}$$

$$\begin{aligned} &\sigma \left[u_{22}(1-(1-p)(1-q^c)) + u_{11}(1-p)(1-q^c) \right] + \\ &(1-\sigma) \left[p(1-q^{nc})u_{21} + pq^{nc}u_{22} + (1-p)q^{nc}u_{12} + (1-p)(1-q^{nc})u_{11} \right] - D(p) \\ &\geq \max_{x\in[0,1]} x(1-\bar{q})u_{21} + x\bar{q}u_{22} + (1-x)\bar{q}u_{12} + (1-x)(1-q)u_{11} - D(x) \end{aligned} \tag{29}$$

The individual rationality constraint (27) is convex by linearity. Because the agent's expected utility function is concave in p, the incentive constraint (28) is equivalent to the following first-order condition which is obviously satisfied on a convex set of incentive schemes:

$$\sigma(1-q^c)(u_{22}-u_{11})+(1-\sigma)[(1-q^{nc})(u_{21}-u_{11})+q^{nc}(u_{22}-u_{12})]=D'(p) \tag{30}$$

Finally, the proof that the collusion constraint in (29) is convex is identical to the proof that (15) is convex.

Let's write down the Lagrangian for this problem with Lagrange multipliers $\bar{\lambda},\bar{\eta}\geq 0$, and $\bar{\delta}$:

$$\begin{aligned}
&\mathcal{L}\left(u_{21},u_{22},u_{12},u_{11},\bar{\lambda},\bar{\delta},\bar{\eta};p,q^c,q^{nc},\sigma\right)=\\
&\sigma\left[(1-(1-p)(1-q^c)h(v_{22})+(1-p)(1-q^c))h(v_{11})\right]+\\
&(1-\sigma)\left[pq^{nc}h(v_{22})+p(1-q^{nc})h(v_{21})+(1-p)q^{nc}h(v_{12})+(1-p)(1-q^{nc})h(v_{11})\right]\\
&-\bar{\delta}\left[\sigma(1-q^c)(u_{22}-u_{11})+(1-\sigma)[(1-q^{nc})(u_{21}-u_{11})+q^{nc}(u_{22}-u_{12})]-D'(p)\right]\\
&-\bar{\lambda}\left(\sigma[u_{22}(1-(1-p)(1-q^c))+u_{11}(1-p)(1-q^c)]+\right.\\
&\left.(1-\sigma)[p(1-q^{nc})u_{21}+pq^{nc}u_{22}+(1-p)q^{nc}u_{12}+(1-p)(1-q^{nc})u_{11}]-D(p)-\underline{u}\right)\\
&-\bar{\eta}\left(\sigma[u_{22}(1-(1-p)(1-q^c))+u_{11}(1-p)(1-q^c)]\right.\\
&+(1-\sigma)[p(1-q^{nc})u_{21}+pq^{nc}u_{22}+(1-p)q^{nc}u_{12}+(1-p)(1-q^{nc})u_{11}]-D(p)\\
&\left.-\max_{x\in[0,1]}\{x(1-\bar{q})u_{21}+x\bar{q}u_{22}+(1-x)\bar{q}u_{12}+(1-x)(1-q)u_{11}-D(x)\}\right)
\end{aligned} \tag{31}$$

Let x^* be the agent's optimal effort if she refuses to share information, i.e.:

$$(u_{21}-u_{11})(1-\bar{q})+(u_{22}-u_{12})\bar{q}=D'(x^*) \tag{32}$$

Then differentiating the Lagrangian with respect to the payoffs we obtain the following first-order conditions:

$$h'(u_{21})=\bar{\lambda}+\frac{\bar{\delta}}{p}+\bar{\eta}\left[1-\frac{x^*(1-\bar{q})}{p(1-\sigma)(1-q^{nc})}\right] \tag{33}$$

$$h'(u_{22})=\bar{\lambda}+\bar{\delta}\frac{\sigma(1-q^c)+(1-\sigma)q^{nc}}{p\bar{q}+\sigma(p(1-q^c)+(1-p)q^c)}+\bar{\eta}\left[1-\frac{x^*\bar{q}}{p\bar{q}+\sigma(p(1-q^c)+(1-p)q^c)}\right] \tag{34}$$

$$h'(u_{12})=\bar{\lambda}-\frac{\bar{\delta}}{1-p}+\bar{\eta}\left[1-\frac{(1-x^*)\bar{q}}{(1-p)(1-\sigma)q^{nc}}\right] \tag{35}$$

$$h'(u_{11})=\bar{\lambda}-\frac{\bar{\delta}}{1-p}+\bar{\eta}\left[1-\frac{1-x^*}{1-p}\right] \tag{36}$$

If $\sigma=0$, then $\bar{q}=q^{nc}$. By inspecting the first- order conditions it is easy to establish the following ordering: $u_{21}=u_{21}>u_{11}=u_{12}$.

If $\sigma>0$, then we need to consider two possible cases: (i) $\bar{\eta}=0$: the collusion constraint (29) is not binding or is just binding; (ii) $\bar{\eta}>0$: the collusion constraint is binding.

When $\bar{\eta} = 0$, then (35) and (36) imply that $u_{12} = u_{11}$. Comparing (33) and (34) it is easy to see that $u_{21} > u_{22}$ (note that $\bar{\delta} > 0$, because otherwise $p = 0$). It is also easy to see that $u_{22} > u_{12}$. Consequently, we have: $u_{21} > u_{22} > u_{12} = u_{11}$.

When $\bar{\eta} > 0$, (35) and (36) imply that $u_{12} \leq u_{11}$. Notice that $u_{22} \geq \max\{u_{21}, u_{12}\}$ cannot be true, because in this case the collusion constraint is not binding. Also, $u_{22} < \min\{u_{21}, u_{12}\}$ is impossible because in this case the collusion constraint cannot hold. Since $v_{11} \geq v_{11}$ it cannot be true that $v_{12} \geq v_{22} \geq v_{21}$ either, because in this case the agent will not take any effort, i.e. $p = 0$. Thus, we have $v_{21} > v_{22} > v_{12}$. Using this ordering in (30) and (32) we conclude that $x^* > p$.

It remains to prove that $v_{22} > v_{11}$. By comparing (33) and (34) it is easy to establish that $v_{21} > v_{22}$ implies $\bar{\delta} < \bar{\eta}(x^* - p)$. Applying this inequality in (34) and (36) one can demonstrate that $h'(v_{22}) - h'(v_{11}) > 0$.
QED.

Proof of Lemma 5:

By definition, $G^{cc}(p|q^c, q^{nc}, \sigma)$ is equal to the value of the objective function in the constraint minimization problem. The objective function in (26) is continuous in all of its arguments. All the constraints are continuous are upper and lower hemi-continuous in (p, q^c, q^{nc}, σ). Then, by Berge's Maximum theorem $G^{CC}(p|\sigma, q^c, q^{nc})$ is continuous. Applying the envelope theorem in (31), we have:

$$\frac{dG^c(p|.)}{dp} = \frac{\partial \mathcal{L}(p|.)}{\partial p} = \sigma(1 - q^c)(h(u_{22}) - h(u_{11}))$$
$$+ (1 - \sigma)[q^{nc}(h(v_{22}) - h(v_{12})) + (1 - q^{nc})(h(v_{21}) - h(v_{11}))] + \bar{\delta} D''(p) > 0$$

Using a similar argument we can show that $G^{nc}(p|q^c, q^{nc}, \sigma)$ is continuous in all arguments except at $\sigma = 0$. The discontinuity is due to the difference between the no-collusion constraint (15) for the case of $\sigma > 0$, and the no-collusion constraint (16) for the case of $\sigma = 0$. Specifically, consider the limit of (15) as σ converges to zero:

$$v_{21} p^{nc}(1 - q^c) + v_{12}(1 - p^{nc}) q^c \geq v_{22}(p^{nc}(1 - q^c) + (1 - p^{nc}) q^c) \tag{37}$$

Obviously, it is different from (16) are different. unless $q^c = q^{nc}$).

To establish that $G^{nc}(p|q^c, q^{nc}, \sigma)$ is increasing (in the case $\sigma > 0$) differentiate (21) to obtain:

$$\frac{dG^{nc}(p^{nc}|.)}{dp^{nc}} = \frac{\partial \mathcal{L}^{*\mathcal{NC}}(.)}{\partial p^{nc})}$$
$$= \bar{q}[h(v_{22}) - h(v_{12})] + (1 - \bar{q})[h(v_{21}) - h(v_{11})] + \delta D''(p^{nc}) > 0$$

QED.

Proof of lemma 6 We want to show that if $\sigma < \underline{\sigma} > 0$, then $V^{nc}(p|q^c, q^{nc}, \sigma) < V^c(p|q^c, q^{nc}, \sigma)$ for all values of p, q^c, q^{nc} that may be optimal. The proof will be given in a series of claims.

Claim 1. If the firm B has rational beliefs about the firm A's strategy and induces its agent to share information, $\exists \underline{q}^c > 0$ s.t. the optimal effort $q^c > \underline{q}^c > 0$.

The maximum effort that the firm A will induce from its agent does not exceed $\bar{p} < 1$ s.t. $D'(\bar{p}) = \pi_{21} - \pi_{11}$.

To induce its agent to exchange information, the firm B can offer an incentive scheme such that $v_{21} = v_{22} > v_{11} = v_{12}$. In this case, agent B's effort q^c is at least as large as q where:

$$(1 - \bar{p})](v_{22} - v_{11}) = D'(q)$$

Since (i) $D'(0) = 0$, b) $h'(\underline{u}) < \infty$, c) $\pi_{21} > \pi_{22} > \pi_{12} \geq \pi_{11}$, $\exists k > 0$ s.t. the firm B will prefer to set $v_{22} - v_{11} > k > 0$, which implies that $q^c > \underline{q}^c > 0$ where

$$(1 - \bar{p})]k = D'(\underline{q}^c)$$

Claim 2. If the firm B has rational beliefs about the firm A's strategy and induces its agent to refuse to share information, $\exists \underline{q}^{nc} > 0$ s.t. the optimal effort $q^c > \underline{q}^{nc} > 0$.

To induce its agent to refuse to share information, the firm B can offer an incentive scheme such that $v_{21} > v_{22} = v_{11} = v_{12}$. In this case, agent B's effort q^{nc} is at least as large as q where:

$$(1 - \bar{p})(v_{21} - v_{11}) = D'(q)$$

Similarly to the previous claim, we can show that $\exists m > 0$ s.t. the firm B finds it optimal to set $v_{21} - v_{11} > m > 0$. Then, $q^{nc} > \underline{q}^{nc} > 0$ where

$$(1 - \bar{p})m = D'(\underline{q}^{nc})$$

Let $\underline{q} = \min(\underline{q}^{nc}, \underline{q}^c)$ Claim 3. For any $p < \bar{p}$ and $q^c \geq \underline{q}$, $q^{nc} \geq \underline{q}$, let $\hat{G}^{nc}(p|q^c, q^{nc}, \sigma)$ be the firm A's cost when its cost-minimization problem (denoted by $\hat{NC}(p|q^c, q^{nc}, \sigma)$) is subject to the agent's individual rationality constraint (14), incentive constraint under no information sharing (13)and the following modified no-collusion constraint:

$$(u_{21} - u_{22})p(1 - \underline{q}) \geq (u_{22} - u_{12})(1 - p)\underline{q} \tag{38}$$

Then $G^{nc}(p|q^c, q^{nc}, \sigma) \geq \hat{G}^{nc}(p|q^c, q^{nc}, \sigma)$.

This claim follows because $\underline{q} = \min(\underline{q}^{nc}, \underline{q}^c)$. Then, if the firm's incentive scheme satisfies the relevant no-collusion constraint (i.e. either (15) or (16)), it also satisfies (38).

Claim 4. For any $p < \bar{p}$ and $q^c \geq \underline{q}$, $q^{nc} \geq \underline{q}$, $\hat{G}^{nc}(p|q^c, q^{nc}, 0) - G^c(p|q^c, q^{nc}, 0) = d > 0$ This claim is obvious because the additional constraint (38) is binding in the problem $\hat{NC}(p|q^c, q^{nc}, 0)$: in its absence, the firm A would set $v_{22} = v_{21} > v_{11} = v_{12}$, which is the optimal profile in the incentive scheme $CC(p|q^c, q^{nc}, 0)$.

By continuity, $\exists \hat{\sigma} > 0$ s.t. $\hat{G}^{nc}(p|q^c, q^{nc}, \hat{\sigma}) - G^c(p|q^c, q^{nc}, \hat{\sigma}) > \frac{d}{2}$, and using claim 3, $G^{nc}(p|q^c, q^{nc}, \hat{\sigma}) - G^c(p|q^c, q^{nc}, \hat{\sigma}) > \frac{d}{2}$

Claim 5. $\exists \underline{\sigma}$ s.t. when $\sigma < \underline{\sigma}$, then $V^{nc}(p|q^{nc}, q^c, \sigma) < V^c(p|q^{nc}, q^c, \sigma)$.

When σ converges to zero, the difference between the expected revenues from the incentive scheme $NC(p|q^c, q^{nc}, \sigma)$ and the incentive scheme $CC(p|q^c, q^{nc}, \sigma)$ converges to zero, while by claim 4, the difference between expected costs is bounded from below a positive number $\frac{d}{2}$. **QED.**

Proof of lemma 8: Consider a game in which firm the B can offer only incentive schemes of type CC, and the firm A can offer only incentive schemes of type NC. It is easy to show that an equilibrium in this game exists. By lemma 4, the firm B randomizes between at most two incentive schemes (indexed by 1 and 2), each consisting of two rewards u^i_H and u^i_L $(i \in \{1,2\})$, The corresponding incentive compatibility constraint of the agent B is: $u^i_H - u^i_L = D'(q_i)$, where q_i is the corresponding effort. Similarly, the firm A randomizes between at most two incentive schemes of class NC.

Now consider the original game in which both firms can offer incentive schemes of both classes. Let us show that, under the conditions of the lemma, neither firm will deviate.

The agent A refuses to exchange information with probability 1. Then the firm B cannot benefit from switching to an incentive scheme of type NC, since this can only increase its cost of inducing effort. Its incentive schemes are optimal in the class CC by construction. Let $\bar{q}$ be the expected value of the agent B's effort. Obviously, $\bar{q} < \hat{p} < 1$ where $\pi_{21} - \pi_{11} = D'(\hat{p})$.

Suppose that the firm A deviates to an incentive scheme of type CC. Then it will offer an incentive scheme $\mathbf{v}$ such that $v_{21} = v_{22} = v_H > v_{12} = v_{11} = v_L$, and the information exchange will occur with probability 1. In this case, the optimal effort p^c is bounded from below by $\underline{p} > 0$, which follows from that fact that $\bar{q} < \hat{p} < 1$ and from the assumption that $(\pi_{22} - \pi_{11})(1 - \hat{p})\epsilon > h\left(D(\epsilon) + \underline{u}\right)$ for some $\epsilon > 0$.

Let $k = \frac{(1-\underline{p})\hat{p}}{\underline{p}(1-\hat{p})}$. We will demonstrate that the firm A will be better off if, instead of $\mathbf{v}$, it offered an incentive scheme $\mathbf{w}$ s.t. $w_{21} = w_{22} = w_{12} = v_H$ and $w_{11} = v_L$. In this case, the agent A's optimal strategy is to refuse to share information and take the same effort p^c. Thus, the firm A has the same expected cost when it offers $\mathbf{w}$ or $\mathbf{v}$.

The difference in expected revenues from $\mathbf{w}$ and $\mathbf{v}$ is equal to:

$$(\pi_{21} - \pi_{22})p(1-q) + (\pi_{12} - \pi_{22})(1-p)q \geq (\pi_{21} - \pi_{22})\underline{p}(1-\bar{q}) + (\pi_{12} - \pi_{22})(1-\underline{p})\bar{q} \geq 0$$

The last inequality is true because $(\pi_{21} - \pi_{22}) \geq k(\pi_{22} - \pi_{12})$. Thus, it is not optimal for the firm A to deviate to an incentive scheme of type CC.

QED.

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