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On information sharing and incentives in R&D

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I investigate the issue of endogenous spillover of R&D information across firms through information exchange between their employees. Although the firms typically cannot observe and restrict communication between their employees in a direct way, they can regulate information flows through the incentive schemes offered to the employees. This article focuses on two issues: characterization of the optimal incentive schemes, and the link between the nature of the firms' interaction in the product market and the intensity of information exchange between the employees.

1. Introduction

■ Both casual observation and empirical evidence suggest that the exchange of technological information between engineers and scientists employed by different firms is a common and widespread phenomenon. A number of studies have found that it plays an important role in the development and dissemination of technical knowledge. von Hippel (1987) reports that informal know-how trading is extensive in semiconductor manufacturing, aerospace, and steel minimill industries in the United States. According to Rogers (1982, p. 106), exchange of information between employees of different firms constitutes "a dominant and distinguishing characteristic of the environment" in the microprocessor industry of the Silicon Valley. Schrader (1991) reports the results of a survey of technical managers indicating that 85% of all respondents have been asked for specific technical information by colleagues working for other firms, and only 2% had never provided the requested information. According to this survey, information received from colleagues working for other firms ranked as the second-most important source of technical knowledge in the steel minimill industry. Only information obtained from colleagues within the same firm was on average seen to be more important.

The empirical studies raise two important questions. First, do the firms benefit from this information exchange, or are they negatively affected? Second, how and to what extent can the firms control it? According to these studies, it is hard or even impossible to monitor such information exchange or control it directly. There are two main reasons for this. On the one hand, a large number of communication channels—including electronic and published media, conferences, meetings, and trade shows—are available to the employees. On the other hand,

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direct ways of regulating and/or preventing information exchange, such as patents and trade-secret policies, are usually not very effective.

As far as patents are concerned, the following two problems significantly diminish their scope and firms' willingness to use them. First, patenting an innovation requires 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. In this case, the firm either will be unable to use its innovation at all, or will have to cross-license it with firms holding related patents, which will dilute the potential value of an innovation. These considerations lead to the conclusion that "patents are not an effective means of preventing information exchange" (Rogers, 1982, p. 119).

The use and the scope of trade-secret policies are also limited. This is due in part to the inability of the courts to establish a clear and unambiguous criterion distinguishing an employer's "know-how" protectable as a "trade secret" from the employees' general knowledge that they are free to discuss and disseminate (see Feldman, 1994). Establishing such a criterion has turned out to be problematic, because the courts have to maintain a delicate balance between the rights of the firms to appropriate the returns from the innovations and the rights of the employees to use their knowledge and skills. Moreover, employees can use different strategies to circumvent a company's secrecy policies. As pointed out by Rogers (1982, p. 117), "almost every secrecy norm for technological information exchange in a high-technology industry has an equally well-known form of evasion."

As a practical matter, contracts restricting an employee from participating in the mainstream forms of scientific communication are not enforceable in court, nor are they even desirable for the firms. Firms benefit from this communication when it involves exchange of general, nonproprietary information and enhances the productivity and/or morale of its employees.

However, employees may also share specific knowledge and product information, which would cause the spillover of innovations and affect firms' product lines and profits even in the short run. This article is concerned with information exchange of this kind and attempts to provide answers to the following questions. How would the firms' behavior be affected by the possibility of such information exchange? When would firms try to encourage or prevent it? In the absence of direct methods of control, can firms regulate information flows between employees indirectly by affecting their behavior through compensation schemes? What is the structure of the optimal compensation schemes, and how does this structure and the intensity of information exchange depend on the nature of the firms' interaction in the product market? Finally, can the observed compensation methods be interpreted as an optimal response by firms to the possibility of information exchange between their employees?

I address these issues in a duopoly framework in which the firms are subject to dual moral hazard: an employee's effort and her participation in information exchange with an employee of the other firm are not observable. The model of information exchange, although special, is motivated by the stylized facts and patterns of behavior described in the empirical literature.[1] First of all, I assume reciprocity in information exchange. Employees can only exchange information; they cannot buy or sell it. Second, the value of information that the employees provide to each other is uncertain at the time of exchange. Third, information exchanged by the employees is hard: if an employee decides to participate in information exchange, she cannot distort the information that she has or reveal it only partially. A detailed explanation of these assumptions is provided in the next section. In modelling the contract-offer game, I follow the approach of maintaining that a contract between a firm and its employee is unobservable to outsiders because of the possibility of secret contract renegotiation (see Katz (1991) for a discussion of this issue). Therefore, contracts do not have any signalling role in this framework.

The first issue explored in this article is the design of optimal compensation schemes. I show that any optimal incentive scheme belongs to one of the two classes characterized below. Incentive

[1] Besides the already mentioned studies, see also Saxenian (1994).

schemes of the first (second) class induce an employee to take a certain effort and agree (refuse) to participate in information exchange with probability 1.

To prevent its employee from participating in information exchange, a firm has to incorporate relative performance evaluation in the compensation structure and make payments to the employee contingent on the qualities of its and the other firm's products. The employee receives lower payments when the two products are of the same or similar qualities, because such similarity indicates that information exchange could have taken place.

Interestingly, optimal incentive schemes that induce an employee to participate in information exchange in most cases also use relative performance evaluation, but for a different reason. It reduces the employee's free-riding on the other employee's effort, and therefore lowers the firm's cost of eliciting effort under information exchange.

Direct forms of relative performance evaluation are not very common in the real world. However, when a firm's profits depend on the qualities of both firms' products, it can achieve the same result by offering a compensation scheme contingent on the quality of the employee's product and the firm's profits. This conclusion suggests an important reason why firms commonly offer profit-sharing plans, such as incentive stock options, to their engineering and research staff. Profit sharing may be the key instrument allowing the firms to control information exchange between their employees. Accordingly, the increasing popularity of incentive stock options may be complementary to the dramatic increase in employees' communication abilities via the Internet and other electronic media.

To reiterate the point, I do not mean to suggest that firms will or can prevent any exchange of information between employees across firms. However, it is a concern for firms that such communication would not be limited to general nonproprietary information and knowledge, but would also involve sharing specific and valuable information about current innovations and products. I demonstrate that by designing compensation schemes appropriately, firms can regulate the exchange of such information. Under what conditions the firms will prevent or encourage it, and hence when the spillover of proprietary information will or will not take place, are the central issues explored here.

A number of factors influence a firm's decision whether or not to prevent information exchange. Let us start from the cost of providing incentives to employees. To prevent information exchange, a firm has to use relative performance evaluation and, therefore, bear an additional cost of compensating risk-averse employees for a higher variance in the reward structure. On the other hand, under information exchange an employee can free-ride and use the R&D results of the other employee as her own. This free-riding has a negative effect on the employee's effort and raises the firm's cost of eliciting it. In most cases, the free-riding effect dominates and makes preventing information exchange more attractive for the firm. This effect is also very strong when the employees are risk neutral but have limited liability.

Due to its reciprocal nature, information exchange will not occur if just one of the firms prevents its employees from participating in it. The second firm can free-ride on the first firm in the provision of incentives and avoid both the cost of preventing information exchange and the cost associated with its employee's free-riding. This second firm incurs the lowest possible cost of inducing effort. Therefore, the firms will use asymmetric strategies whenever information exchange is prevented with probability 1. This result fits very well with the observation that a variety of compensation schemes for engineers and technical employees is typically used in the high-tech industries. Obviously, each firm would prefer to be in the position of the free-rider, which gives rise to a coordination problem. Failure of coordination between firms may result in mixed-strategy equilibria in which each firm prevents its employees from participating in information exchange with some probability.

Although cost considerations play an important role in determining whether information exchange does or does not occur, the key factor is the nature of the firms' interaction in the product market. Not surprisingly, I find that information exchange is prevented when competition between the firms is intense. When firms compete head-to-head in the market, eliminating the spillover of innovations is critically important, because it gives each firm a chance to attain technological leadership and take the upper hand in the competition.

Somewhat more surprisingly, information exchange is also prevented when an innovation developed by one firm can easily be imitated by the other firm. In this case, information sharing between the employees does not generate any benefit for the firms, while preventing it eliminates the employees' free-riding and therefore reduces the firms' cost of inducing effort. Thus, we should expect that information exchange will be prevented in environments where patent protection is weak or imitation is easy.

On the other hand, in many situations the firms benefit from information exchange between the employees, because it gives them an indirect access to the R&D results of the other firms and, net of the free-riding effect, makes their employees more knowledgeable and productive. The benefits of information exchange dominate when competition between the firms is not intense. In particular, information exchange will take place when the firms serve different markets or produce differentiated products.

Still, the employees' free-riding on each other's effort reduces the benefit of information exchange and may offset it completely, especially if the employees enjoy limited liability. In the latter case, even in the absence of competition between the firms, information exchange will take place only if the premium that the market pays for high quality is not too large.

The issues of information sharing in R&D and incentives for knowledge transfer have been previously studied in the literature, particularly in the context of licensing (e.g., d'Aspremont, Bhattacharya, and Gérard-Varet, 2000; Bhattacharya, Glazer, and Sappington, 1992; Katz and Shapiro, 1987), and research joint ventures (e.g., d'Aspremont and Jacquemin, 1988; Katz, 1986; Kamien, Muller, and Zang, 1992). The diffusion of R&D information is discussed by Reinganum (1989). This article can be seen as complementary to the existing literature. It examines knowledge transfer that takes place at an intermediate stage of the R&D process in the presence of asymmetric information, and it explores alternative channels for it that arise in the agency context. Thus, this article offers an endogenous explanation of information spillovers that are not subject to the firms' control. R&D spillovers controlled by the firm have been studied by Choi (1993) and De Fraja (1993).

This article is also related to the literature on cooperation between agents working for the same principal (Holmström and Milgrom, 1990; Itoh, 1991, 1993; Macho-Stadler and Pérez, 1993; Ramakrishnan and Thakor, 1991). This literature examines optimal incentives to induce cooperation and demonstrates that cooperation not only brings technological advantages, but also allows the agents to share risk, and therefore reduces the firm's cost of providing incentives (Itoh, 1993; Ramakrishnan and Thakor, 1991). The situation considered in this article is different, because information is a public good and the agents incur no direct cost when they exchange it. They would cooperate unless induced not to do so by the firms. The problem here is too much cooperation, rather than too little.

This article also contributes to our understanding of collusion and strategic-delegation problems. In the case of observable contracts, delegation has been studied by Fershtman and Judd (1987), Spencer and Brander (1983), Brainard and Martimort (1996), Kühn (1997), and others. For more on collusion, see Laffont and Martimort (1998).

The rest of the article is organized as follows. Section 2 develops the model. Section 3 characterizes optimal incentive schemes. Section 4 establishes the existence of equilibria and characterizes equilibrium outcomes. In Section 5, I consider the case where the employees are risk neutral but have limited liability.

2. Model

■ Two firms, A and B, operate in the market. Each firm hires an employee (an engineer or researcher) to undertake R&D and develop/design a new product. An employee is referred to as "she" and is also indexed by A or B. The new product can be of high (θ_2) or low (θ_1) quality. Firms are risk neutral and employees are risk averse, except in Section 5 where I assume that the employees are risk neutral and have limited liability. Table 1 represents the firms' profits gross of

TABLE 1

Qualities of the Products	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}

compensation costs as a function of the qualities of their products, with the first (second) element in the pair standing for the quality of firm A's (B's) product. All the profit levels are assumed to be nonnegative and satisfy the following partial ordering: $\pi_{21} > \max\{\pi_{12}, \pi_{11}\}$, $\pi_{22} \geq \pi_{11}$. This ordering is intuitive. It is natural to expect that a firm with a high-quality product competing against a rival with a low-quality product would enjoy higher profits than a firm with a low-quality product (independent of the quality of the rival's product), and that profits when both firms have high-quality products are higher than when both firms have low-quality products.

Probability p $(q) \in [0, 1]$ that the product developed by employee A (B) is of high quality depends on the unobservable effort taken by this employee. Using a reparameterization, we can consider that, instead of efforts, employees directly choose these probabilities. Let $D(p)$ $(D(q))$ denote the cost to employee A (B) of effort/probability p (q). $D(\cdot)$ is assumed to be twice continuously differentiable, nonnegative, increasing, and convex, i.e., $\forall\ p \in (0, 1]$ $D(p) \geq 0$, $D'(p) > 0$, and $D''(p) > 0$. I also assume that $D(0) = 0$, $D'(0) = 0$, and, to guarantee an interior solution, $\lim_{p\to 1} D(p) = \infty$.

Each firm can at least deliver a low-quality product to the market, either because a firm has a low-quality design prior to hiring an employee, or because developing a low-quality product requires a fixed and verifiable amount of effort that the firm can elicit from the employee by imposing large penalties for failing to produce it. Both interpretations fit the model equally well.

The employees are risk averse and have identical utility functions $u(w) - D(e)$ separable in income w and effort e. The income utility function $u(\cdot)$ is twice continuously differentiable, strictly increasing, and concave. Also, assume that $\lim_{w\to\infty} u'(w) = 0$. Under these assumptions, the inverse function $h(s) \equiv u^{-1}(s)$ is well defined, increasing, convex, and measures the monetary cost of providing the employee with utility level s. An employee's reservation utility level is denoted by $\underline{u}$. I assume that $\underline{u}$ is nonnegative and not too large, i.e., $\exists\ \epsilon > 0$, s.t. $(\pi_{21} - \pi_{11})(1 - \hat{p})\epsilon > h(D(\epsilon) + \underline{u})$, where $\hat{p} < 1$ is s.t. $h'(D(\hat{p}) + \underline{u})D'(\hat{p}) = \pi_{21} - \pi_{11}$. The last assumption implies that each firm will induce its employee to take a positive effort.

The timing of events is as follows. At first, each firm offers an incentive scheme to its employee. This incentive scheme is not observed by the other firm or its employee. If the employee accepts it, she takes her R&D effort to design the product. Each employee also decides, without observing the other employee's effort, whether to participate in information exchange. If both employees have agreed to do so, they share the results of their R&D with each other. Finally, each employee submits her design to her firm. The firm uses this design to manufacture its product and brings it to market, where profits are realized.

The R&D process and information exchange can formally be represented as follows. There is a set Ω (of measure 1) of possible states of the world. The true state of the world $\bar{\omega}$ is unknown and is learned only when the products are brought to the market. Each element ω in set Ω is equally likely to be the true state of the world. In the course of her R&D activity, an employee explores some subset of Ω and designs a product that will work well (will be of high quality) if $\bar{\omega}$ is in this subset of Ω. If an employee explores a subset of measure s, she incurs cost $D(s)$ and develops a product that is of high quality with probability s.

Information exchange increases the probability that an employee's product will be of high quality. Information is assumed to be "hard," i.e., if the employees agree to exchange information, they cannot distort or disclose it only partially. Therefore, after information exchange both products will be of high quality if the true state of the world $\bar{\omega}$ is in the subset explored by at least one of the employees. The employees cannot coordinate beforehand what subsets of Ω to explore. Consequently, if employees A and B explore subsets of measure p and q respectively and exchange information, both products will be of high quality with probability $1-(1-p)(1-q)$, and of low quality with the complementary probability.

The specific modelling assumptions regarding information exchange are introduced for several reasons. First, as mentioned above, they reflect the stylized facts described in the empirical literature. Second, there are natural justifications for making them. Third, they make the model tractable.

Reciprocity of information exchange is a norm in the high-tech industry. According to Rogers (1982, p. 114), the rule of the game is that "information must be given in order for it to be obtained." An obvious reason why information has to be exchanged rather than bought or sold is the difficulty of negotiating a payment for it. Another reason lies in the legal and contractual restrictions that prohibit selling information. When the penalties are sufficiently large, an employee may be reluctant to sell information even if the probability of detection is small.[2] Selling information may also have a negative effect on an employee's reputation.

Reputational effects and technological indivisibilities can explain why information cannot be distorted or disclosed partially. Since new product designs become observable when they are brought to the market, the fact that a person has presented incomplete or distorted information to a colleague will be detected eventually, which can cause other colleagues to suspend future cooperation with the "cheat." Refusal to share information is not likely to have such an effect, since it will not be seen as "cheating." In high-tech industries, especially computer-related ones, reputational considerations can play an important role because informal relations between the employees typically last much longer than a spell of employment with a particular firm.[3] But although individual reputations are long-lived, high worker mobility can make it difficult to sustain more complex intertemporal patterns of cooperation, for example, such that the employees do not exchange information but alternate between receiving and providing information unilaterally.[4]

On the other hand, technological indivisibilities can make distorting information too costly, as it may require running another set of experiments, designing another product, or writing another computer program.

The assumption that the value of information is uncertain at the time of exchange is quite natural, because the value of information depends on the quality of the product developed on its basis. Often, the quality of a new product can be recognized only after it is brought to the market. Another way to justify this assumption is to note that an employee typically has knowledge about only a part of a new product or process, and the extent to which her knowledge is valuable depends on the design of the other parts.

Let me now turn to the contractibility assumptions. I assume that a firm can offer an incentive scheme that is contingent on qualities of both products. Equivalently, payments to an employee can be contingent only on the firm's profits if there is a one-to-one relation between the firm's profits and the qualities of both products or, if this relation is not one-to-one, on the firm's profits and the quality of the employee's product. Accordingly, incentive schemes offered by firms A

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[2] Recently, a federal grand jury in the United States indicted Jose Ignacio Lopez, a former General Motors and Volkswagen top purchasing manager, for allegedly stealing secret GM design documents and turning them over to rival Volkswagen. Lopez's career was essentially ruined after the matter came to light in 1993. In 2000, Lucent Technologies filed a lawsuit accusing ten former workers of revealing proprietary information to their new employer, Cisco Systems, which recruited them with significantly higher compensation offers.

[3] According to Saxenian (1994), in Silicon Valley high rates of mobility and job switching coexist with stability of informal networks. As put by Floyd Kramme of National Semiconductor: "It's an industry where everybody knows everybody because at one time or another everyone worked together" (Braun and Macdonald, 1978, p. 135).

[4] Formally, consider an economy where the individuals from a large population are matched randomly in every period, so that the chance that any two individuals are matched more than once is small, but their reputations persist in the population.

and B can be represented by 4-tuples of utility levels $(v_{21}, v_{22}, v_{12}, v_{11})$ and $(u_{21}, u_{22}, u_{12}, u_{11})$ respectively. Table 2 summarizes the payoffs that the employees get when they do and do not exchange information.

3. Optimal incentive schemes

■ Turning to the formal analysis of the model, consider, at first, the employees' behavior in the continuation game after they have accepted the incentives schemes. It is shown in the Appendix that any optimal strategy of employee A (B) can be represented as a triple $(p^c, p^{nc}, \delta) \in [0, 1]^3$ $((q^c, q^{nc}, \sigma) \in [0, 1]^3)$, which stands for the following. With probability δ (σ) employee A (B) takes effort p^c (q^c) and agrees to exchange information. With probability $1 - \delta$ $(1 - \sigma)$ employee A (B) takes effort p^{nc} (q^{nc}) and refuses to exchange information.

Now let us consider the firms' problem. Suppose that firm A offers incentive scheme $(v_{21}, v_{22}, v_{12}, v_{11})$, and employee A (B) follows strategy (p^c, p^{nc}, δ) $((q^c, q^{nc}, \sigma))$. Let $\bar{p} = p^c\delta + p^{nc}(1 - \delta)$ and $\bar{q} = q^c\sigma + q^{nc}(1 - \sigma)$. Then firm A's expected payoff is equal to

$$\begin{aligned}
&(1 - \delta)[p^{nc}(1 - \bar{q})(\pi_{21} - h(v_{21})) + p^{nc}\bar{q}(\pi_{22} - h(v_{22})) \\
&\quad + (1 - p^{nc})\bar{q}(\pi_{12} - h(v_{12})) + (1 - p^{nc})(1 - \bar{q})(\pi_{11} - h(v_{11}))] \\
&\quad + \delta(1 - \sigma)[p^c(1 - q^{nc})(\pi_{21} - h(v_{21})) + p^c q^{nc}(\pi_{22} - h(v_{22})) \qquad (1) \\
&\quad + (1 - p^c)q^{nc}(\pi_{12} - h(v_{12})) + (1 - p^c)(1 - q^{nc})(\pi_{11} - h(v_{11}))] \\
&\quad + \delta\sigma[(1 - (1 - p^c)(1 - q^c))(\pi_{22} - h(v_{22})) + (1 - p^c)(1 - q^c)(\pi_{11} - h(v_{11}))].
\end{aligned}$$

The incentive scheme offered by firm A is optimal if it maximizes (1) taking into account that employee A's strategy maximizes her payoff given this incentive scheme. Since the contracts are unobservable by a third party, firm A's incentive scheme cannot affect the strategy of employee B. Similarly, neither firm A nor employee A observes the incentive scheme offered by firm B or employee B's strategy, although in equilibrium firm A and employee A share the same beliefs about them. Therefore, firm A's profit-maximization problem can be decomposed into two parts:[5]

(i) Cost minimization: For any strategy (p^c, p^{nc}, δ), derive an incentive scheme that induces employee A to follow this strategy at the minimal expected cost to firm A under given beliefs about employee B's strategy.

(ii) Profit maximization: Using the cost function derived in the first step, find an optimal strategy (p^c, p^{nc}, δ) that maximizes firm A's expected profits.

Naturally, the same applies to the optimal strategy of firm B. In the remainder of this section I will characterize optimal incentive schemes by solving the cost-minimization part of the firm's problem. Since the two firms are identical, the discussion will focus on firm A.

Let us, at first, introduce one important simplification. Suppose it is optimal for firm A to offer incentive scheme $\mathcal{I} = \{v_{21}, v_{22}, v_{12}, v_{11}\}$ that induces its employee to randomize by choosing strategy (p^c, p^{nc}, δ) s.t. $\delta \in (0, 1)$. Obviously, employee A gets the same payoff whether she takes effort p^c and agrees to exchange information (action C), or takes effort p^{nc} and refuses to exchange information (action NC). Firm A must also be indifferent between these two actions of its employee, because otherwise incentive scheme $\mathcal{I}$ would not be optimal for it. To see this, suppose that firm A gets a strictly higher payoff when its employee takes action NC. Then it would be optimal for firm A to increase v_{21} (v_{12}) slightly if $p^{nc} \geq p^c$ $(p^{nc} < p^c)$. Inspection of (A1) and (A2) in the Appendix reveals that this modification induces employee A to refuse to exchange information and to choose an effort close to p^{nc}. Similarly, if firm A obtains a higher payoff when employee A takes action C, then it would be optimal for this firm to prevent information exchange by increasing v_{22} slightly when $p^c\bar{q} + \sigma((1 - p^c)q^c + p^c(1 - q^c)) \geq p^{nc}\bar{q}$, and increasing v_{11} slightly in the opposite case.

[5] This method is due to Grossman and Hart (1983).

TABLE 2

	Utility Levels (No Information Exchange)		Utility Levels (Information Exchange)	
Qualities	Employee A	Employee B	Employee A	Employee B
(θ_2, θ_1)	v_{21}	u_{12}	v_{22}	u_{22}
(θ_1, θ_2)	v_{12}	u_{21}	v_{22}	u_{22}
(θ_2, θ_2)	v_{22}	u_{22}	v_{22}	u_{22}
(θ_1, θ_1)	v_{11}	u_{11}	v_{11}	u_{11}

This observation implies that an employee's randomization can be replaced by its firm's randomization in the following way. Let $\mathcal{I}'$ and $\mathcal{I}''$ be two identical copies of incentive scheme $\mathcal{I}$. Suppose that employee A takes action C when offered $\mathcal{I}'$ and takes action NC when offered $\mathcal{I}''$. Obviously, these strategies are optimal for the employee, and firm A is indifferent between offering $\mathcal{I}'$ or $\mathcal{I}''$. If it offers $\mathcal{I}'$ with probability δ and $\mathcal{I}''$ with probability $1 - \delta$, then the induced distribution of employee A's actions does not change.

Thus, we can assume without loss of generality that the employee never randomizes in the decision to exchange or not to exchange information, and can restrict the analysis to two classes of incentive schemes. Incentive schemes of class *CC* (*NC*) minimize the firm's expected cost of inducing the employee to take the desired effort and agree (refuse) to exchange information. In the sequel, we will continue to use the notation (p^c, p^{nc}, δ) to describe the employee's strategy with the understanding that it should be interpreted as follows: with probability δ $(1 - \delta)$ the firm offers incentive scheme of class *CC* (*NC*) inducing the employee to agree (refuse) to exchange information and take effort p^c (p^{nc}). The following lemma summarizes this discussion.

Lemma 1. Without loss of generality, any incentive scheme offered by a firm belongs to either class *CC* or class *NC*.

A typical element of class *NC* is incentive scheme $NC(p \mid q^c, q^{nc}, \sigma)$, which minimizes the firm's cost of inducing its employee to take effort p and refuse to exchange information given the strategy (q^c, q^{nc}, σ) of the other employee. This incentive scheme is characterized in the following lemma.

Lemma 2. Incentive scheme $NC(p \mid q^c, q^{nc}, \sigma)$ is unique. If $p > 0$, the elements of this incentive scheme satisfy the following ordering: $v_{21} > v_{22} > v_{12} \geq v_{11}$. The last inequality is nonstrict if and only if either $\sigma = 0$ or $q^c = 0$.

Proof. See the Appendix.

Obviously, an employee would be willing to exchange information if her payoff depended only on the quality of her product, i.e., if $v_{21} = v_{22}$ and $v_{12} = v_{11}$. To eliminate the incentives for information exchange, the firm has to offer higher payments when the two products are of different qualities and set $v_{21} > v_{22}$ and $v_{12} \geq v_{11}$. This has the desired effect, because the products can be of different qualities only if no information exchange has taken place. Thus, relative performance evaluation is necessary to prevent information exchange between the employees. It has been demonstrated (Itoh, 1991; Macho-Stadler and Pérez, 1993) that relative performance evaluation can induce cooperation between the employees. Here it serves the opposite goal.

Next, I characterize incentive schemes of class CC. Let $CC(p \mid q^c, q^{nc}, \sigma)$ be the incentive scheme that minimizes the firm's cost of inducing its employee to take effort p and agree to exchange information given that the other employee follows strategy (q^c, q^{nc}, σ).

Lemma 3. Incentive scheme $CC(p \mid q^c, q^{nc}, \sigma)$ is unique. Its elements are ordered in the following way: $v_{21} \geq v_{22} > v_{11} \geq v_{12}$.

Proof. See the Appendix.

The proof shows that $v_{21} = v_{22}$ if and only if $\sigma = 0$ or 1, while $v_{12} = v_{11}$ if $\sigma = 0$ or 1, or if the employee strictly prefers to exchange information. Thus, relative performance evaluation is also optimal when the firm encourages information exchange. This may appear surprising, because an employee will certainly agree to exchange information if her compensation depends only on the quality of her product. Yet such an incentive scheme is not optimal.

The firm sets $v_{21} > v_{22}$, because an increase in v_{21} is a more cost-effective way to induce effort than an increase in v_{22}. To demonstrate this formally, let $Q(v_{21})$ ($Q(v_{22})$) be the ratio of the coefficient on $h(v_{21})$ ($h(v_{22})$) in the firm's expected cost function to the coefficient on v_{21} (v_{22}) in the employee's incentive constraint (see the Appendix). This ratio reflects the firm's marginal cost of inducing effort via the corresponding element of the incentive scheme. We have

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

i.e., the firm gets a bigger "bang for the buck" by increasing v_{21}. The effect of an increase in v_{22} on effort is smaller, because as a result of information exchange employee A obtains payment v_{22} even if her own design is of low quality, but employee B's design is of high quality. Therefore, employee A can exert a low effort but free-ride on the other employee's effort and still have a good chance of earning v_{22}.

On the other hand, an employee cannot obtain v_{21} by free-riding. She gets this payoff only if she develops a high-quality product, and the other employee refuses to exchange information but ends up developing a low-quality product. It follows that setting $v_{21} > v_{22}$ is optimal. However, an employee who has taken a sufficiently high effort may refuse to share information if $v_{21} - v_{22}$ is sufficiently large. To prevent this and to ensure that information exchange remains more profitable for the employee, the firm may have to set $v_{12} < v_{11}$.

Let $G^{nc}(p \mid q^c, q^{nc}, \sigma)$ ($G^c(p \mid q^c, q^{nc}, \sigma)$) denote the expected cost of incentive scheme $NC(p \mid q^c, q^{nc}, \sigma)$ ($CC(p \mid q^c, q^{nc}, \sigma)$) to the firm. These cost functions are characterized in the following lemma.

Lemma 4. Cost function $G^c(p \mid q^c, q^{nc}, \sigma)$ is continuous in all of its arguments and increasing in p. Cost function $G^{nc}(p \mid q^c, q^{nc}, \sigma)$ is increasing in p and continuous in all arguments everywhere except at $\sigma = 0$.

Proof. See the Appendix.

Although the discontinuity of $G^{nc}(p \mid q^c, q^{nc}, \sigma)$ at $\sigma = 0$ could potentially create equilibrium existence problems, this does not happen because the discontinuity occurs at an irrelevant point of the action space. This is demonstrated in the proof of Theorem 1 in the Appendix.

A firm's revenue is linear in its employee's effort. However, $G^{nc}(p \mid \cdot)$ and $G^c(p \mid \cdot)$ are not necessarily convex in p on all the domain. Therefore, in equilibrium the firms may have to randomize between several incentive schemes of the same class. Since the expected payoffs of a firm and its employee depend only on the expected values of the other employee's strategy, such randomization does not cause any changes in my analysis. However, we need to bear in mind that q^c and q^{nc} in $G^{nc}(p \mid q^c, q^{nc}, \sigma)$ and $G^c(p \mid q^c, q^{nc}, \sigma)$ should be interpreted as expected values of the other employee's efforts.[6]

4. Equilibria

■ In this section I establish the existence of equilibria and demonstrate how their properties, in particular the intensity of information exchange, depend on the nature of the firms' interaction

[6] For example, if $G^{nc}(q \mid \cdot)$ is concave in q if $q \in [q_1, q_2]$ for some $q_1, q_2 \in [0, 1]$, then it cannot be optimal for firm B to offer incentive scheme $NC(q' \mid \cdot)$ for some $q' \in (q_1, q_2)$. However, if firm B randomizes between $NC(q_1 \mid \cdot)$ and $NC(q_2 \mid \cdot)$ by choosing the first incentive scheme with probability $t \in (0, 1)$ s.t. $q' = tq_1 + (1 - t)q_2$, then the payoffs of firm A and its employee depend only on q'.

in the product market. This analysis provides an endogenous explanation of the spillover effect in the R&D.

Existence of an equilibrium will be established differently in two separate cases. In the case $\pi_{22} < \pi_{12}$, pure-strategy equilibria will be exhibited in Proposition 3. In the case $\pi_{22} \geq \pi_{12}$, a general existence proof is provided in the following theorem.

Theorem 1. Suppose that $\pi_{22} \geq \pi_{12}$. Then there exists an equilibrium in the incentive-scheme game between the firms.

Proof. See the Appendix.

Before attempting to characterize the equilibria, let us review the factors determining whether the firm prevents its employee from participating in information exchange. Clearly, each firm benefits from such information exchange, because it provides an indirect access to the results of R&D performed at the other firm. However, this benefit may be outweighed by the other factors.

On the cost side, an employee's free-riding on information provided by the other employee raises the firm's effective cost of effort under information exchange. At the same time, when the employees are risk averse, a firm preventing information exchange incurs an extra cost of compensating its employee for the additional variability in the payoff structure generated by the relative performance evaluation. In most cases, the first effect dominates the second effect.

Yet the factor that plays the most important role in determining whether information exchange does or does not occur is the nature of the firms' interaction in the product market. Analyzing all possible market structures would be too cumbersome. Instead, in several propositions below I examine a number of interesting economic environments, which allows me to draw sufficiently general conclusions about the incidence of information exchange.

I use ratio $R = (\pi_{21} - \pi_{22})/(\pi_{22} - \pi_{12})$ to measure the competitiveness of the environment and the tradeoff that affects the decision whether to prevent or to encourage information exchange. The numerator of R can be interpreted as a premium for the technological leadership. It represents the benefit of preventing information exchange for the firm whose employee develops a high-quality product when the competitor's employee fails to develop such a product. On the other hand, the denominator of R represents the benefit of information exchange for the firm when its employee fails to develop a high-quality product and the other firm's employee succeeds in this. Intuitively, it is clear that the firm has stronger incentives to prevent information exchange when R is high. This intuition is confirmed in the following two propositions.

Proposition 1. Information exchange is prevented with a positive probability if $R \geq 1$.

Proof. See the Appendix.

To understand this proposition, suppose that there exists an equilibrium in which information exchange takes place with probability 1. Without loss of generality, in this equilibrium with a positive probability employee A takes effort p that is (weakly) higher than employee B's expected effort q^e. Then firm A can get a higher payoff by deviating and preventing information exchange. Its cost of inducing effort p will go down, because the cost reduction from eliminating the employee's free-riding dominates the additional cost of preventing information exchange. At the same time, $R > 1$ implies that firm A's expected revenue will go up. To see this, combine $p \geq q^e$ with the fact that the maximal possible benefit of information exchange $\pi_{22} - \pi_{12}$ is less than the premium for technological leadership $\pi_{21} - \pi_{22}$.

The condition $R > 1$ may not be sufficient for the existence of an equilibrium in which information exchange is prevented with probability 1, because the firms could randomize between incentive schemes of classes *CC* and *NC*. However, as R increases, the premium for the technological leadership becomes sufficiently high compared to the benefit of information exchange. Beyond a certain point, a firm would rather incur the cost of preventing information exchange than randomize and miss a chance to become a technological leader. This is the intuition behind the following proposition.

Proposition 2. Let $\pi_{22} - \pi_{11} > \underline{K}$, and $\max\{\pi_{21}, \pi_{22}\} < \overline{K}$, for some $\underline{K}$, $\overline{K}$ such that $0 < \underline{K}, \overline{K} < \infty$. Then $\exists\, k > 0$ s.t. if $R \geq k$, then there exists an equilibrium in which information exchange is prevented with probability 1.

Proof. See the Appendix.

In an equilibrium with no information exchange, only one firm offers an incentive scheme of class *NC* that uses relative performance evaluation. The other firm free-rides and offers an incentive scheme of class *CC* in which, according to Lemma 3, the payments to the employee depend only on the quality of this employee's product. This result helps to explain the nonuniformity of compensation schemes across the firms in the same industry. It also suggests that the firm that commits to a compensation structure earlier, say, due to its incumbency position, can free-ride and save the cost of preventing information exchange. The incumbent firm would offer an incentive scheme consisting of a base salary and quality premia, whereas a recent entrant would have to offer a profit-sharing plan to its employees to prevent information exchange. Although there may be multiple equilibria, equilibria of this type have a focal nature because neither firm randomizes between incentive schemes of different classes.

Next, let us consider differentiated Bertrand competition. In this case, a firm earns positive profits when the quality of its product is different from the quality of the competitor's product, and zero profits otherwise. Such a payoff structure is characteristic of markets where the firms compete by setting prices and the consumers differ in their willingness to pay for quality. The firm offering a high- (low-)quality product captures the upper (lower) end of the market when the competitor offers a product of different quality. Formally, the payoffs are ordered in the following way:

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

Proposition 3. In the case of differentiated Bertrand competition, there exists an equilibrium in which information exchange is prevented with probability 1.

Proof. See the Appendix.

By Lemma 2, the firm that prevents information exchange offers an incentive scheme with the following reward structure: $v_{21} > v_{22} > v_{12} > v_{11}$. In the context of differentiated Bertrand competition, a payment to the employee in this incentive scheme can be represented as a sum of two parts: (i) a quality premium and (ii) a share of profits.

Let v_{11} be the base pay. Then $v_{22} - v_{11}$ is a premium for a high-quality product. Increment $v_{21} - v_{22}$ is a share of profit π_{21} paid when the firm captures the high end of the market, and increment $v_{12} - v_{11}$ is a share of profit π_{12} paid when the firm captures the low end of the market. When the firm delivers a product of the same quality as its competitor, it does not earn any profits, and therefore the employee does not get any payoff from profit sharing.

Thus, in contrast to standard moral hazard arguments, this article suggests that the firms may be offering profit sharing not to elicit effort, but rather to regulate information flows and prevent the spillover of information through communication between the employees. When information exchange is not a concern, effort could be elicited more effectively by offering performance-related bonuses that are not based on relative performance evaluation. The most common and popular methods of profit sharing are incentive stock options and employee stock purchase plans (known as ISOP and ESPP). Since the stock price normally reflects the firm's profitability and its relative performance vis-à-vis its competitors, these stock plans can generate the desired incentive effect and prevent an employee from sharing critical information.

Let us now consider environments where competition between the firms is less intense. At first, suppose that a firm can duplicate or reengineer an innovation developed by the other firm without violating the patents or other intellectual property rights. In the high-tech industry, "inventing around a patent" is commonly used to reproduce inventions legitimately in a modified form. In this case, the following result holds.

Proposition 4. Suppose that a firm can reengineer an innovation developed by the competitor at a sufficiently small cost. Then there exists an equilibrium in which information exchange between the employees is prevented with probability 1.

Proof. When a firm can reengineer an innovation at zero cost, the payoffs have the following structure: $\pi_{21} = \pi_{22} = \pi_{12} > \pi_{11}$. In this case, existence of an equilibrium in which information exchange is prevented with probability 1 can be established by modifying the proof of Proposition 2. If a firm incurs cost $c > 0$ to reengineer an innovation, inspection of the proof of Proposition 2 shows that the result holds by continuity as long as c is sufficiently small. *Q.E.D.*

The intuition behind this result is easy to understand. Suppose that firm B does not prevent information exchange, and consider the tradeoff that firm A faces in this case. The value of learning about firm B's innovation through information exchange does not exceed the cost c of reengineering it. At the same time, by preventing information exchange the firm reduces its cost by a positive amount, because the additional cost of relative performance evaluation is strictly less than the eliminated cost of the employee's free-riding. Then preventing information exchange is optimal for firm A as long as c is sufficiently small.

Finally, suppose that the two firms operate in different markets separated either geographically or through product differentiation.[7] In this case, a firm's revenue will not be significantly affected by the quality of the other firm's product. To measure the degree to which the revenue of one firm is independent of the other firm's product I use ratio $\kappa_I \equiv \max\{| \pi_{21} - \pi_{22} |, | \pi_{12} - \pi_{11} |\}/(\pi_{21} - \pi_{11})$. Let us say that the market interaction between the firms is weak (strong) if κ_I is small (large).[8] Then the following result holds.

Proposition 5. If the market interaction between the firms is sufficiently weak, i.e., κ_I is small enough, then information exchange takes place with probability 1 in all equilibria.

Proof. See the Appendix.

When the market interaction between the firms is weak, information exchange produces a significant benefit on the revenue side because it raises the probability that the firm delivers a high-quality product without diluting the value of its own innovation. This positive effect outweighs the negative effect of information exchange on the cost of eliciting effort. Note that coefficient R is also small when k_I is small, but the opposite is not true.

It is straightforward to extend this proposition to show that information exchange also takes place in the following two cases: (i) negative externality on the "loser": $\pi_{21} - \pi_{22}$ is small and $\pi_{12} < \pi_{11}$; (ii) positive externality on the "loser": $\pi_{21} - \pi_{22}$ is small, $\pi_{22} > \pi_{12} > \pi_{11}$, and π_{11} is not too low. In the first case, the proof of Proposition 5 applies without change, while in the latter case a simple modification of the proof is needed.

It is interesting to consider the relation between information exchange and licensing. Licensing allows the firms to share the results of R&D *ex post*, as the licensing firm (licensor) grants the other firm (licensee) the right to use its innovation in exchange for a fee. In our context, the licensor is the firm with a high-quality product and the licensee is the firm with a low-quality product. They earn π_{21} and π_{12} respectively in the absence of licensing. If the innovation underlying the high-quality product is licensed, both firms earn π_{22} in the market. Therefore, licensing is efficient when $S \equiv 2\pi_{22} - \pi_{21} - \pi_{12} > 0$, i.e., $R \equiv (\pi_{21} - \pi_{22})/(\pi_{22} - \pi_{12}) < 1$. S represents the surplus from licensing. Since licensing must be beneficial for both firms, the licensing fee must be equal to αS, where $\alpha \in [0, 1]$, implying that the benefit to the licensee is $(1 - \alpha)S$. Then licensing has the following effect on the firms' profits: $\hat{\pi}_{21} = \pi_{21} + \alpha S$, $\hat{\pi}_{12} = \pi_{12} + (1 - \alpha)S$, while π_{22} and π_{11} remain unchanged. As a result, the coefficient R, which prior to licensing is less than one, becomes $\hat{R}(\alpha) = (\pi_{21} - \pi_{22} + \alpha S)/[\pi_{22} - \pi_{12} - (1 - \alpha)S] = 1$ for any α. Proposition 1 implies that in this case information exchange is prevented with a positive probability.

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[7] Also assume that reengineering an innovation is impossible.

[8] In the limit when $\kappa_I = 0$, we have $\pi_{21} = \pi_{22} > \pi_{12} = \pi_{11}$

Since licensing reduces the benefit of information exchange, intuition suggests that the firms would see them as substitutes. The results of the article can be used to confirm this intuition in the following case. Suppose that the market payoffs satisfy the conditions of Proposition 5 or its extensions. Then in the absence of licensing, information exchange will occur with probability 1, whereas if licensing takes place, information exchange will be prevented with a positive probability because $\hat{R}(\alpha) = 1$.

5. Limited liability

■ In this section I consider the case of risk-neutral employees who have limited liability, so that all payments by the firms must be nonnegative. In this case, it becomes possible to compute the firms' cost functions explicitly and isolate the factors discussed in the previous sections. More important, there are certain differences between the results of this and previous sections, which implies that limited liability can have important implications for information exchange.

For simplicity, let us also assume that an employee's reservation utility level $\underline{u}$ is equal to zero. Then we can compute the following cost functions (see the Appendix):

$$G^{nc}(p \mid q^c, q^{nc}, \sigma) = D'(p)p \qquad \forall\, \sigma \in [0, 1]$$

$$\begin{cases} G^c(p \mid q^c, q^{nc}, 0) = D'(p)p \\ G^c(p \mid q^c, q^{nc}, 1) = D'(p)\left(p + \dfrac{q^c}{1 - q^c}\right) \\ G^c(p \mid q^c, q^{nc}, \sigma) = D'(p)p + \sigma q^c v_{22} \qquad \text{if } \sigma \in (0, 1), \text{ where } 0 < v_{22} \leq \dfrac{D'(p)}{1 - \sigma q^c}. \end{cases}$$

Since the employees are risk neutral, the variability in the payoff structure has no effect on their expected payoffs. Therefore, preventing information exchange is not costly for a firm, and we have $G^{nc}(p \mid q^c, q^{nc}, \sigma) = G^c(p \mid q^c, q^{nc}, 0)\ \forall\, \sigma \in (0, 1)$. Then an equilibrium in which both firms prevent information exchange always exists.

On the other hand, under information exchange the employees' free-riding generates an additional cost equal to $G^c(p \mid q^c, q^{nc}, 1) - G^{nc}(p \mid q^c, q^{nc}, \sigma) = D'(p)\frac{q^c}{1-q^c}$. Information exchange can be sustained in equilibrium only if this additional cost does not exceed the expected benefit that the firms get from access to each other's innovations.

In this section I shall study how this tradeoff is resolved in different situations. The analysis will focus on the existence of a "cooperative" equilibrium in which the probability of information exchange is equal to one. For technical convenience, I assume that $D'''(p) \geq 0$. Under this assumption, if a "cooperative" equilibrium exists, it is unique and symmetric. In it, each firm earns the following payoff:

$$U^c(p^c, p^c) \equiv \pi_{22}\left(1 - (1 - p^c)^2\right) + \pi_{11}(1 - p^c)^2 - D'(p^c)\left(p^c + \frac{p^c}{1 - p^c}\right),$$

where "cooperative" effort p^c induced by each firm solves

$$(\pi_{22} - \pi_{11})(1 - p^c) = D''(p^c)\left(p^c + \frac{p^c}{1 - p^c}\right) + D'(p^c). \tag{2}$$

This will be an equilibrium outcome if and only if no firm has an incentive to deviate and prevent information exchange, i.e., $U^c(p^c, p^c) \geq U^{nc}(p^d, p^c)$, where

$$U^{nc}(p^d, p^c) \equiv \pi_{21}p^d(1 - p^c) + \pi_{22}p^d p^c + \pi_{12}(1 - p^d)p^c + \pi_{11}(1 - p^d)(1 - p^c) - D'(p^d)p^d.$$

p^d is the optimal "noncooperative" effort for the deviator. It solves

$$(\pi_{21} - \pi_{11})(1 - p^c) + (\pi_{22} - \pi_{12})\, p^c = D''(p^d)p^d + D'(p^d). \tag{3}$$

The following necessary conditions for the existence of a "cooperative" equilibrium are derived from $U^c(p^c, p^c) - U^{nc}(p^c, p^c) \geq 0$. To obtain the second condition I also use (2).

Condition 1. $2\pi_{22} - \pi_{21} - \pi_{12} > D'(p^c)/(1 - p^c)^2$.

Condition 2. If $\exists\, k > 0$ s.t. $\forall\, p \in [0, 1]$ $D'(p) \geq (k/2)D''(p)p$, then

$$2\pi_{22} - \pi_{21} - \pi_{12} > \frac{1}{(k + 1)}(\pi_{22} - \pi_{11}).$$

Condition 1 simply says that the benefit of information exchange for the firm must be greater than the extra cost generated by the employees' free-riding. Note that the cost of free-riding is negligible when p^c is low, but it grows at a faster rate than p^c. Therefore, the "cooperative" equilibrium fails to exist when p^c is sufficiently high.

Since p^c is endogenous, Condition 2 provides a useful extension of Condition 1. It depends exclusively on the parameters of the problem, i.e., the market payoffs and the cost function. According to Condition 2, cooperative equilibrium fails to exist when $\pi_{22} - \pi_{11}$ is sufficiently large, because in this case p^c and, hence, the cost of free-riding are high. Thus, cooperative equilibrium may fail to exist even if $\pi_{22} \geq \pi_{21} > \pi_{12}$, i.e., when there are obvious gains to cooperation.

Let us now turn to the sufficient conditions. We have the following proposition.

Proposition 6. $\exists\, K > 0$, $b > 0$, and $r \in (0, 1)$ s.t. cooperative equilibrium exists if (i) $\max\{\pi_{21}, \pi_{22}\} \leq K$, (ii) $(\pi_{22} - \pi_{12})/(\pi_{21} - \pi_{11}) \geq b$, and (iii) $(\pi_{22} - \pi_{11})/(\pi_{22} - \pi_{12}) \geq r$.

Proof. See the Appendix.

Condition (i) guarantees that p^c and p^d are sufficiently low, so that free-riding costs are small. Conditions (ii) and (iii) together ensure that the positive effect of information exchange on the firm's revenue is sufficiently large.

The necessary conditions indicate that despite the benefits of information exchange on the revenue side, the cooperative equilibrium may still be nonsustainable due to a high cost of free-riding. To get a better understanding of this issue, consider the following case where the benefit of information exchange is obvious: $\pi_{22} = \pi_{21} = \pi_H$ and $\pi_{12} = \pi_{11} = \pi_L$.

Proposition 7. Suppose that $\pi_{22} = \pi_{21} = \pi_H$ and $\pi_{12} = \pi_{11} = \pi_L$, and the cost function $D(p)$ is such that $D'(p)/D''(p) \geq ah(p)$, where $a > 0$ and $h(p)$ is an (weakly) increasing function. Then $\exists\, K_L$ and K_H, $K_H \geq K_L > 0$, s.t. cooperative equilibrium exists if $\pi_H - \pi_L \leq K_L$, and fails to exist if $\pi_H - \pi_L \geq K_H$.

Proof. See the Appendix.

By Proposition 5, in the absence of limited liability exchange of information always takes place under the payoff structure considered in Proposition 7. The result of Proposition 7 is different because the cost of free-riding is higher under limited liability. To overcome free-riding and stimulate effort, the firm can either raise the payments to the employee for a high-quality product or lower the payments for a low-quality product. Under limited liability, the second option is no longer available, and the firm has to raise the rewards for high quality, which leads to higher costs. As p^c increases, the cost of free-riding explodes because it grows at a faster rate than $D'(p^c)$. Therefore, when $\pi_H - \pi_L$ and hence p^c are sufficiently high, it becomes less costly for the firm to achieve the same probability of innovation that is obtained under information exchange, namely $p^c + p^c(1 - p^c)$, by preventing information exchange and inducing the employee to take this effort on her own.

To summarize, Proposition 7 demonstrates that in the agency framework, information exchange could lead to such high levels of free-riding that it becomes optimal to prevent cooperation even if the firms do not compete in the market. This implication is quite intriguing because it casts doubt on the classical proposition that cooperation in R&D improves efficiency.

Proposition 7 has another important implication. Consider a family of cost functions $tD(p)$ indexed by $t > 0$, where $D(p)$ satisfies the condition of Proposition 7. t can be interpreted as a measure of technical complexity of R&D. Since p^c decreases in t, Proposition 7 can be used to show that "cooperative" equilibrium exists when t is sufficiently large and fails to exist when t is small. Thus, information exchange is more likely in industries where technical problems are highly complex and R&D is very costly, so that a typical firm cannot afford the expenses required to ensure a high probability of discovering an innovation. On the other hand, when R&D costs are low, it is more cost-effective for the firm to pay its employees for a high effort rather than encourage information exchange. Although this logic may appear straightforward, the intuition relies on the fact that the free-riding costs rise at a faster rate than an employee's effort.

6. Conclusions

■ In recent years, firms in the high-tech industries have adopted many innovative compensation methods. One unorthodox approach proposed recently is to give the employees stock options in competing firms and in customer firms.[9] This article suggests that such trends in compensation could be complementary to the dramatic increase in the employees' communication abilities that have been expanded by the Internet and other electronic media.

A classical proposition in the R&D literature is that a lack of cooperation causes duplication and excessive levels of R&D, and is detrimental for efficiency. This article suggests that an agency structure of the firms can be responsible for lack of cooperation, even if on the revenue side there are obvious benefits from cooperation for all participants.

This research can be extended in several directions. First, in certain environments information exchange may involve partial or one-sided revelation of information and/or side payments between employees. Second, employees could also coordinate their efforts *ex ante* and avoid duplication prior to information exchange. Third, it would be interesting to consider the environments with many firms where the issues of coalition formation arise and additional incentives for information exchange may be present, such as not being left out of cooperation involving other firms and their employees.

Appendix

■ Proofs of Lemmas 2–4, Propositions 1–3 and 5–7, Theorem 1, and a characterization of the employees' optimal strategies follow.

□ **Characterization of the employees' optimal strategies.** Suppose that employee B uses strategy $(F_B(q), \tau(q))$, where $F_B(q)$ denotes probability distribution over efforts, and $\tau(q)$ stands for the probability that employee B agrees to exchange information when she takes effort q. Employee B's expected effort is equal to $\bar{q} = \int_0^1 q\,dF_B(q)$, the unconditional probability that she agrees to exchange information is $\sigma = \int_0^1 \tau(q)dF_B(q)$, and her expected effort given that she agrees (refuses) to exchange information is equal to $q^c = (1/\sigma)\int_0^1 q\tau(q)dF_B(q)$ ($q^{nc} = [1/(1-\sigma)]\int_0^1 q(1-\tau(q))dF_B(q)$).

Given employee B's strategy, employee A obtains the following expected payoffs when she takes effort p:

(i) If she refuses to exchange information,

$$U^{nc}(p,\bar{q}) \equiv p\bar{q}v_{22} + p(1-\bar{q})v_{21} + (1-p)\bar{q}v_{12} + (1-p)(1-\bar{q})v_{11} - D(p). \tag{A1}$$

(ii) If she agrees to exchange information,

$$U^c(p,q^c,q^{nc},\sigma) \equiv \sigma[(1-(1-p)(1-q^c))v_{22} + (1-p)(1-q^c)v_{11}]$$

[9] "Competing Shares." *Wall Street Journal*, May 16, 2000, p. B20

$$+ (1-\sigma)[pq^{nc}v_{22} + p(1-q^{nc})v_{21} + (1-p)q^{nc}v_{12} + (1-p)(1-q^{nc})v_{11}] - D(p). \tag{A2}$$

$U^{nc}(p, \bar{q})$ and $U^c(p, q^c, q^{nc}, \sigma)$ are strictly concave in p, and therefore they have unique maximizers p^{nc} and p^c respectively. If $U^c(p^c, q^c, q^{nc}, \sigma) > U^{nc}(p^{nc}, \bar{q})$, employee A's unique optimal action is to take effort p^c and agree to exchange information. If $U^c(p^c, q^c, q^{nc}, \sigma) < U^{nc}(p^{nc}, \bar{q})$, her unique optimal action is to take effort p^{nc} and refuse to exchange information. Finally, both actions are optimal when $U^c(p^c, q^c, q^{nc}, \sigma) = U^{nc}(p^{nc}, \bar{q})$. Let δ denote the probability that employee A chooses the first action. It follows that the triple (p^c, p^{nc}, δ) provides a complete description of employee A's optimal strategy. The same is true for employee B.

Proof of Lemma 2. Suppose that employee B is expected to follow strategy (q^c, q^{nc}, σ). Let $\bar{q} = \sigma q^c + (1-\sigma)q^{nc}$. By Lemma 1, incentive scheme $NC(p \mid q^c, q^{nc}, \sigma)$ can be derived by solving the following optimization problem:

Problem NC: $(p \mid q^c, q^{nc}, \sigma)$.

$$\min_{(v_{21}, v_{22}, v_{12}, v_{11})} p\bar{q}h(v_{22}) + p(1-\bar{q})h(v_{21}) + (1-p)\bar{q}h(v_{12}) + (1-p)(1-\bar{q})h(v_{11}) \tag{A3}$$

subject to the incentive constraint,

$$p = \arg\max_{x\in[0,1]} x\bar{q}v_{22} + x(1-\bar{q})v_{21} + (1-x)\bar{q}v_{12} + (1-x)(1-\bar{q})v_{11} - D(x), \tag{A4}$$

the individual-rationality constraint,

$$p\bar{q}v_{22} + (1-p)\bar{q}v_{21} + (1-p)\bar{q}v_{12} + (1-p)(1-\bar{q})v_{11} - D(p) \geq \underline{u}, \tag{A5}$$

and the no-collusion constraint,

(a) if $\sigma > 0$,

$$\begin{aligned} &p\bar{q}v_{22} + p(1-\bar{q})v_{21} + (1-p)\bar{q}v_{12} + (1-p)(1-\bar{q})v_{11} - D(p) \\ &\quad \geq \max_{z\in[0,1]} \sigma[(1-(1-z)(1-\bar{q}^c)v_{22} + (1-z)(1-\bar{q}^c)v_{11}] \\ &\quad\quad + (1-\sigma)\left[z\bar{q}^{nc}v_{22} + z(1-\bar{q}^{nc})v_{21} + (1-z)\bar{q}^{nc}v_{12} + (1-z)(1-\bar{q}^{nc})v_{11}\right] - D(z) \end{aligned} \tag{A6}$$

(b) if $\sigma = 0$,

$$p(1-\bar{q})v_{21} + (1-p)\bar{q}v_{12} \geq (p(1-\bar{q}) + (1-p)\bar{q})\, v_{22}. \tag{A7}$$

The no-collusion constraints (A6) and (A7) guarantee that the employee does not agree to exchange information. Condition (A7) is imposed as a refinement that eliminates equilibria in which the employees use weakly dominated strategies, and each of them refuses to exchange information only because she expects the other to do so. Formally, condition (A7) is necessary if the employees make small trembles in the implementation of their strategies.

I solve the problem for $\sigma > 0$. In the case $\sigma = 0$, the solution is similar. To show that the problem has a unique solution, let us establish that it is convex in the vector of rewards. The objective function and the individual-rationality constraint (A5) are obviously convex. It is also easy to show that (A6) is convex. Strict concavity of the employee's expected utility function in p implies that incentive constraint (A4) can be replaced by the following first-order condition, which is linear in the rewards:

$$(v_{21} - v_{11})(1-\bar{q}) + (v_{22} - v_{12})\bar{q} = D'(p). \tag{A8}$$

Next, let z^* be the unique maximizer of the expression on the right-hand side of (A6). Differentiating the Lagrangian of this problem with nonnegative multipliers λ, κ, and η on individual-rationality, incentive, and no-collusion constraints respectively, I obtain the following first-order conditions:

$$h'(v_{21}) = \lambda + \frac{\kappa}{p} + \eta\left[1 - \frac{z^*(1-\sigma)(1-\bar{q}^{nc})}{p(1-\bar{q})}\right] \tag{A9}$$

$$h'(v_{22}) = \lambda + \frac{\kappa}{p} + \eta\left[1 - \frac{z^*\bar{q} + \sigma\,(z^*(1-q^c) + (1-z^*)q^c)}{p\bar{q}}\right] \tag{A10}$$

$$h'(v_{12}) = \lambda - \frac{\kappa}{1-p} + \eta\left[1 - \frac{(1-z^*)(1-\sigma)\bar{q}^{nc}}{(1-p)\bar{q}}\right] \tag{A11}$$

$$h'(v_{11}) = \lambda - \frac{\kappa}{1-p} + \eta\left[1 - \frac{1-z^*}{1-p}\right]. \tag{A12}$$

Let us establish that $\eta > 0$, i.e., constraint (A6) is binding. Suppose otherwise. Then from (A9)–(A12) it follows that $v_{21} = v_{22} > v_{12} = v_{11}$. But then (A6) fails, a contradiction.

Individual-rationality constraint (A5) must also be binding, because otherwise all rewards can be reduced by some $\epsilon > 0$. By (A9) and (A10),

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

Hence, $v_{21} > v_{22}$. But then we must have $v_{12} < v_{22}$, because otherwise the no-collusion constraint (A6) will not be binding. Comparison of (A11) and (A12) implies that $v_{12} \geq v_{11}$. This inequality is strict when $(1-\sigma)q^{nc} < \bar{q}$, i.e., $\sigma q^c > 0$.

Finally, let us establish that $z^* < p$. By (A6), z^* solves

$$(1-\sigma)\left((v_{21} - v_{11})(1-q^{nc}) + (v_{22} - v_{12})q^{nc}\right) + \sigma(v_{22} - v_{11})(1-q^c) = D'(z^*).$$

Then by (A8), $D'(p) - D'(z^*) = \sigma\,((v_{21} - v_{22})(1-q^c) + (v_{22} - v_{12})q^c) > 0.$ *Q.E.D.*

Proof of Lemma 3. According to Lemma 1, incentive scheme $CC(p \mid q^c, q^{nc}, \sigma)$ can be derived by solving the following constrained minimization problem.

Problem CC: $(p \mid q^c, q^{nc}, \sigma)$.

$$\begin{aligned} \min_{(v_{21}, v_{22}, v_{12}, v_{11})} \;& \sigma\left[h(v_{22})(1-(1-p)(1-q^c)) + h(v_{11})(1-p)(1-q^c)\right] \\ &+ (1-\sigma)\left[h(v_{22})pq^{nc} + h(v_{21})p(1-q^{nc}) + h(v_{12})(1-p)q^{nc} + h(v_{11})(1-p)(1-q^{nc})\right] \end{aligned} \qquad \text{(A13)}$$

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

$$\begin{aligned} &\sigma\left[v_{22}(1-(1-p)(1-q^c)) + v_{11}(1-p)(1-q^c)\right] \\ &\quad + (1-\sigma)\left[p(1-q^{nc})v_{21} + pq^{nc}v_{22} + (1-p)q^{nc}v_{12} + (1-p)(1-q^{nc})v_{11}\right] - D(p) \geq \underline{u} \end{aligned} \qquad \text{(A14)}$$

$$\begin{aligned} p = \arg\max_{x\in[0,1]} &\{\sigma\left[v_{22}(1-(1-x)(1-q^c)) + v_{11}(1-x)(1-q^c)\right] \\ &+ (1-\sigma)\left[x(1-q^{nc})v_{21} + xq^{nc}v_{22} + (1-x)q^{nc}v_{12} + (1-x)(1-q^{nc})v_{11}\right] - D(x)\} \end{aligned} \qquad \text{(A15)}$$

$$\begin{aligned} &\sigma\left[v_{22}(1-(1-p)(1-q^c)) + v_{11}(1-p)(1-q^c)\right] \\ &\quad + (1-\sigma)\left[p(1-q^{nc})v_{21} + pq^{nc}v_{22} + (1-p)q^{nc}v_{12} + (1-p)(1-q^{nc})v_{11}\right] - D(p) \\ &\quad \geq \max_{x\in[0,1]} x(1-\bar{q})v_{21} + x\bar{q}v_{22} + (1-x)\bar{q}v_{12} + (1-x)(1-q)v_{11} - D(x). \end{aligned} \qquad \text{(A16)}$$

Incentive constraint (A15) is equivalent to the following first-order condition:

$$\sigma(1-q^c)(v_{22} - v_{11}) + (1-\sigma)[(1-q^{nc})(v_{21} - v_{11}) + q^{nc}(v_{22} - v_{12})] = D'(p). \qquad \text{(A17)}$$

To show that this problem is convex, we can use a proof similar to that of Lemma 2. Let x^* be the maximizer of the right-hand side of (A16), i.e., $(v_{21} - v_{11})(1-\bar{q}) + (v_{22} - v_{12})\bar{q} = D'(x^*)$.

When $\sigma < 1$, differentiating the Lagrangian of this problem with multipliers $\gamma, \rho \geq 0$, and τ respectively on the individual-rationality, incentive, and collusion constraints, we obtain the following first-order conditions:

$$h'(v_{21}) = \gamma + \frac{\tau}{p} + \rho\left[1 - \frac{x^*(1-\bar{q})}{p(1-\sigma)(1-q^{nc})}\right] \qquad \text{(A18)}$$

$$h'(v_{22}) = \gamma + \tau\frac{\sigma(1-q^c) + (1-\sigma)q^{nc}}{p\bar{q} + \sigma(p(1-q^c) + (1-p)q^c)} + \rho\left[1 - \frac{x^*\bar{q}}{p\bar{q} + \sigma(p(1-q^c) + (1-p)q^c)}\right] \qquad \text{(A19)}$$

$$h'(v_{12}) = \gamma - \frac{\tau}{1-p} + \rho\left[1 - \frac{(1-x^*)\bar{q}}{(1-p)(1-\sigma)q^{nc}}\right] \qquad \text{(A20)}$$

$$h'(v_{11}) = \gamma - \frac{\tau}{1-p} + \rho\left[1 - \frac{1-x^*}{1-p}\right]. \qquad \text{(A21)}$$

First let us consider the case $\sigma = 0$. Then $\bar{q} = q^{nc}$, and by inspecting the above first-order conditions it is easy to establish the following: $v_{21} = v_{22} > v_{12} = v_{11}$.

Suppose now that $0 < \sigma < 1$. Then there are two cases: (i) $\rho = 0$, or (ii) $\rho > 0$. If $\rho = 0$, then $\tau > 0$, because otherwise $p = 0$. Then comparing (A18) and (A19) we get $v_{21} > v_{22}$. Comparing (A20) and (A19), we obtain that $v_{22} > v_{12}$. Finally, by (A20) and (A21), $v_{12} = v_{11}$.

When $\rho > 0$, the collusion constraint is binding and therefore $\max\{v_{21}, v_{12}\} \geq v_{22} \geq \min\{v_{21}, v_{12}\}$. By (A20) and (A21), $v_{11} \geq v_{12}$ (the inequality is strict when $q^c > 0$). Therefore, $v_{21} > v_{12}$ because otherwise the employee will choose effort $p = 0$. Since the collusion constraint is binding, $v_{21} > v_{22}$. Therefore, $v_{22} > v_{12}$ because otherwise the collusion constraint will fail. Then incentive constraints imply that $x^* > p$. Comparing (A18) and (A19), it is easy to establish that $v_{21} > v_{22}$ implies that $\tau < \rho(x^* - p)$. Using this inequality in (A19) and (A21) we obtain $h'(v_{22}) - h'(v_{11}) > 0$, i.e., $v_{22} > v_{11}$.

Finally, consider the case $\sigma = 1$. Then v_{22} and v_{11} are uniquely determined by (A17) and (A14), which must hold as equality. v_{21} and v_{12} are not uniquely determined. In particular, we can set $v_{21} = v_{22}$ and $v_{12} = v_{11}$. *Q.E.D.*

Proof of Lemma 4. At first, let us establish the continuity. By definition, $G^c(p \mid q^c, q^{nc}, \sigma)$ is equal to the value of the minimized objective function in (A13) which is continuous in all the arguments. The corresponding constraints (A14) and (A16) are continuous i.e., upper and lower hemicontinuous in (p, q^c, q^{nc}, σ). Then the continuity of $G^C(p \mid \sigma, q^c, q^{nc})$ follows from Berge's Maximum theorem.

Using a similar argument it is easy to establish that $G^{nc}(p \mid q^c, q^{nc}, \sigma)$ is continuous in all arguments except at $\sigma = 0$. The discontinuity may arise because the no-collusion constraint (A6) in the case of $\sigma > 0$ and the no-collusion constraint (A7) in the case of $\sigma = 0$ are binding, but generically define different subsets in the domain. Specifically, consider the limit of (A6) as σ converges to zero:

$$v_{21}p(1 - q^c) + v_{12}(1 - p)q^c \geq v_{22}(p(1 - q^c) + (1 - p)q^c). \tag{A22}$$

It coincides with (A7) only if $q^c = q^{nc}$.

Next, let us show that both $G^{nc}(p \mid q^c, q^{nc}, \sigma)$ and $G^c(p \mid q^c, q^{nc}, \sigma)$ are increasing in p. The proof is by contradiction. Suppose that $G^{nc}(p_1 \mid q^c, q^{nc}, \sigma) \leq G^{nc}(p_2 \mid q^c, q^{nc}, \sigma)$ for some (q^c, q^{nc}, σ) and $p_1, p_2 \in [0, 1]$ s.t. $p_1 > p_2$. We will demonstrate an incentive scheme $(\tilde{v}_{21}, \tilde{v}_{22}, \tilde{v}_{12}, \tilde{v}_{11})$ that induces the employee to take effort p_2 and refuse to exchange information at a cost to the firm that is less than $G^{nc}(p_2 \mid q^c, q^{nc}, \sigma)$.

Let $(v_{21}, v_{22}, v_{12}, v_{11})$ be incentive scheme $NC(p \mid q^c, q^{nc}, \sigma)$. It satisfies incentive constraint $(v_{21} - v_{11})(1 - \bar{q}) + (v_{22} - v_{12})\bar{q} = D'(p_1)$. Also, by Lemma 2, $v_{21} > v_{22} > v_{12} \geq v_{11}$.

Three possible cases need to be considered:

Case (i). $(v_{21} - v_{11})(1 - \bar{q}) \leq D'(p_2)$. Let $\tilde{v}_{22} = v_{22} - \Delta/p_2$, $\tilde{v}_{12} = v_{12} + \Delta/(1 - p_2)$, where $\Delta > 0$ is chosen to satisfy incentive constraint: $(v_{21} - v_{11})(1 - \bar{q}) + (\tilde{v}_{22} - \tilde{v}_{12})\bar{q} = D'(p_2)$. Note that $\tilde{v}_{22} \geq \tilde{v}_{12}$. It is easy to check that incentive scheme $(v_{21}, \tilde{v}_{22}, \tilde{v}_{12}, v_{11})$ satisfies individual-rationality constraint (A5) and corresponding no-collusion constraint (A6) or (A7). Consider now the firm's expected cost:

$$\begin{aligned} &p_2(1 - \bar{q})h(v_{21}) + p_2\bar{q}h(\tilde{v}_{22}) + (1 - p_2)\bar{q}h(\tilde{v}_{12}) + (1 - p_2)(1 - \bar{q})h(v_{11}) \\ &\quad < p_2(1 - \bar{q})h(v_{21}) + p_2\bar{q}h(v_{22}) + (1 - p_2)\bar{q}h(v_{12}) + (1 - p_2)(1 - \bar{q})h(v_{11}) \\ &\quad - \bar{q}\Delta\left(h'(\tilde{v}_{22}) - h'(\tilde{v}_{12})\right) < G^{nc}(p_1 \mid q^c, q^{nc}, \sigma) \leq G^{nc}(p_2 \mid q^c, q^{nc}, \sigma), \end{aligned} \tag{A23}$$

where the first inequality is true by convexity of $h(\cdot)$, the second inequality is true because $p_1 > p_2$ and $v_{21} > \tilde{v}_{22} \geq \tilde{v}_{12} \geq v_{11}$, and the third inequality is true by assumption.

Case (ii). $\exists\, \hat{t} > 0$ s.t. $v_{21} - \hat{t}/p_2 \geq p_2v_{22} + (1 - p_2)v_{12}$ and $(v_{21} - v_{11} - \hat{t}/[p_2(1 - p_2)])(1 - \bar{q}) = D'(p_2)$. Then let $\tilde{v}_{22} = \tilde{v}_{12} = p_2v_{22} + (1 - p_2)v_{12}$, $\tilde{v}_{21} = v_{21} - t/p_2$ and $\tilde{v}_{11} = v_{11} + t/(1 - p_2)$, where t is chosen to satisfy $(\tilde{v}_{21} - \tilde{v}_{11})(1 - \bar{q}) = D'(p_2)$.

Case (iii). $(v_{21} - v_{11} - t/[p_2(1 - p_2)])(1 - \bar{q}) > D'(p_2)\, \forall\, t > 0$ s.t. $v_{21} - t/p_2 \geq p_2v_{22} + (1 - p_2)v_{12}$. Then, let $\tilde{v}_{21} = \tilde{v}_{22} = \tilde{v}_{12} = p_2v_{22} + (1 - p_2)v_{12} - s/[p_2 + (1 - p_2)\bar{q}]$, $\tilde{v}_{11} = v_{11} + [p_2/(1 - p_2)](v_{21} - p_2v_{22} - (1 - p_2)v_{12}) + s/[(1 - p_2)(1 - \bar{q})]$, where s is such that $(\tilde{v}_{21} - \tilde{v}_{11})(1 - \bar{q}) = D'(p_2)$.

In cases (ii) and (iii) it is easy to show that incentive scheme $(\tilde{v}_{21}, \tilde{v}_{22}, \tilde{v}_{12}, \tilde{v}_{11})$ satisfies individual-rationality and no-collusion constraints. Employing the same techniques as in (A23), it can be demonstrated that the expected cost of this incentive scheme is strictly less than $G^{nc}(p_2 \mid q^c, q^{nc}, \sigma)$, a contradiction. Thus, $G^{nc}(p \mid q^c, q^{nc}, \sigma)$ must be strictly increasing in p. *Q.E.D.*

Proof of Theorem 1. First let us establish that the firms' best-response correspondences are convex. A firm's revenue function is linear in its employee's effort, but $G^{nc}(p \mid \cdot)$ and $G^c(p \mid \cdot)$ are not necessarily convex in p. To convexify them, consider the firms' mixed strategies.

Let $\tilde{G}^{nc}(p \mid \cdot)$ be the convex hull of $G^{nc}(p \mid \cdot)$. By Theorem 2.3 in Rockafeller (1970),

$$\tilde{G}^{nc}(p \mid \cdot) = \min_{p_1, p_2 \in [0,1]: tp_1 + (1-t)p_2 = p} tG^{nc}(p_1 \mid \cdot) + (1 - t)G^{nc}(p_2 \mid \cdot).$$

Similarly, let $\tilde{G}^c(p \mid \cdot)$ be the convex hull of $G^c(p \mid \cdot)$. It is easy to see that both $\tilde{G}^{nc}(p \mid \cdot)$ and $\tilde{G}^c(p \mid \cdot)$ are increasing, continuous, and weakly convex in p. Weak convexity implies that $\tilde{G}^{nc}(p \mid \cdot)$ and $\tilde{G}^c(p \mid \cdot)$ are linear on the intervals where they do not coincide with $G^{nc}(p \mid \cdot)$ and $G^c(p \mid \cdot)$ respectively. Note that q^c and q^{nc} should now also be interpreted as expectations.

Let $V^{nc}(p \mid q^c, q^{nc}, \sigma)$ and $V^c(p \mid q^c, q^{nc}, \sigma)$ denote the corresponding expected profit functions. We have

$$V^{nc}(p \mid q^c, q^{nc}, \sigma) \equiv \pi_{21} p(1-\bar{q}) + \pi_{22} p\bar{q} + \pi_{12}(1-p)\bar{q} + \pi_{11}(1-p)(1-\bar{q}) - \tilde{G}^{nc}(p \mid q^c, q^{nc}, \sigma) \quad \text{(A24)}$$

$$\begin{aligned} V^c(p \mid q^c, q^{nc}, \sigma) \equiv\ & (1-\sigma)[\pi_{21} p(1-q^{nc}) + \pi_{22} pq^{nc} + \pi_{12}(1-p)q^{nc} + \pi_{11}(1-p)(1-q^{nc})] \\ & + \sigma\left[\pi_{22}(1-(1-q^c)(1-p)) + \pi_{11}(1-p)(1-q^c)\right] - \tilde{G}^c(p \mid q^c, q^{nc}, \sigma). \end{aligned} \quad \text{(A25)}$$

Since both (A24) and (A25) are weakly concave, the set of maximizers of $V^{nc}(p \mid \cdot)$ $\left(V^c(p \mid \cdot)\right)$ is either a unique effort p^{nc*} (p^{c*}) or an interval $[p_L^{nc*}, p_H^{nc*}]$ $\left([p_L^{c*}, p_H^{c*}]\right)$. In the latter case, the firm's best-response set includes randomization between incentive schemes. Thus, the best-response correspondence is convex.

Consider 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 get the following payoffs:

$$W_A((p^c, p^{nc}, \delta), (q^c, q^{nc}, \sigma)) \equiv (1-\delta)V^{nc}(p^{nc} \mid q^c, q^{nc}, \sigma) + \delta V^c(p^c \mid q^c, q^{nc}, \sigma) \quad \text{(A26)}$$

$$W_B((q^c, q^{nc}, \sigma), (p^c, p^{nc}, \delta)) \equiv (1-\sigma)V^{nc}(q^{nc} \mid p^c, p^{nc}, \delta) + \sigma V^c(q^c \mid p^c, p^{nc}, \delta). \quad \text{(A27)}$$

Obviously, there is a one-to-one correspondence between the equilibria of game M and the equilibria of the original game. Therefore, the equilibria of the original game can be derived as follows: (i) derive the equilibria of the game M, and (ii) compute incentive schemes used in the corresponding equilibrium of the original game by inverting $\tilde{G}^c(\cdot)$ and $\tilde{G}^{nc}(\cdot)$.

If $\max_p V^{nc}(p \mid q^c, q^{nc}, \sigma) > \max_p V^c(p \mid q^c, q^{nc}, \sigma)$, firm A's best-response set consists of all $(p^{*c}, p^{*nc}, \delta^*)$ s.t. $p^{*c} \in [0,1]$ is arbitrary, $\delta^* = 0$, and $p^{*nc} \in \arg\max_p V^{nc}(p \mid q^c, q^{nc}, \sigma)$. If $\max_p V^{nc}(p \mid q^c, q^{nc}, \sigma) \leq \max_p V^c(p \mid q^c, q^{nc}, \sigma)$, a similar argument can be used to show that the best response set is convex. Thus, firm A's best-response set is convex. By symmetry, the same must be true for firm B.

The following lemma establishes the bounds of the interval in which optimal efforts can lie, and shows that a firm will not offer an incentive scheme of class NC when the other employee agrees to exchange information with a sufficiently small probability, implying that the discontinuity of $G^{nc}(p \mid q^c, q^{nc}, \sigma)$ at $\sigma = 0$ is irrelevant.

Lemma A1. Suppose that $\pi_{22} \geq \pi_{12}$. Then $\exists\ p^{\min}, p^{\max} \in (0,1)$ and $\underline{\sigma} > 0$ s.t.

(i) If strategy (σ, q^c, q^{nc}) is chosen with a positive probability in some equilibrium, then $q^{nc}, q^c \in [p^{\min}, p^{\max}]$.

(ii) $V^{nc}(p \mid q^c, q^{nc}, \sigma) < V^c(p \mid q^c, q^{nc}, \sigma)$ if $p \leq p^{\max}$, $q^c \geq p^{\min}$, $q^{nc} \geq p^{\min}$ and $\sigma \leq \underline{\sigma}$.

Proof. The lemma will be proved in a sequence of steps.

Claim 1. $\exists\ p^{\max} < 1$ s.t. if in some equilibrium effort p is taken with a positive probability, then $p \leq p^{\max}$. Note that $G^{nc}(p \mid q^c, q^{nc}, \sigma) \geq h(\underline{u} + D(p))$ and $G^c(p \mid q^c, q^{nc}, \sigma) \geq h(\underline{u} + D(p))\ \forall\ p, q^c, q^{nc}, \sigma$. Since $\lim_{p \to 1} D(p) = \infty$, and $h(\cdot)$ is convex, $\lim_{p \to 1} h(\underline{u} + D(p)) = \infty$, but the firm's revenue does not exceed π_{21}. This establishes the claim.

Claim 2. $\exists\ \underline{q}^c > 0$ s.t. $\forall\, q \in [0, \underline{q}^c], \delta \in [0,1]$ and $p^c, p^{nc} \in [0, p^{\max}]$, $V^c(2\underline{q}^c \mid p^c, p^{nc}, \delta) > V^c(q \mid p^c, p^{nc}, \sigma)$. Consider $q_2, q_1 \in (0,1)$ s.t. $q_1 \leq q_2/2$. Then

$$\begin{aligned} & V^c(q_2 \mid p^c, p^{nc}, \delta) - V^c(q_1 \mid p^c, p^{nc}, \delta) \\ & \geq \frac{q_2}{2}\left\{(\pi_{21} - \pi_{11})(1-\delta)(1-p^{nc}) + (\pi_{22} - \pi_{12})(1-\delta)p^{nc} + (\pi_{22} - \pi_{11})\delta(1-p^c)\right\} \\ & \quad - G^c(q_2 \mid p^c, p^{nc}, \delta) + G^c(q_1 \mid p^c, p^{nc}, \delta). \end{aligned} \quad \text{(A28)}$$

Thus, it is sufficient to demonstrate that $G^c(q_2 \mid p^c, p^{nc}, \delta) - G^c(q_1 \mid p^c, p^{nc}, \delta)$ is of order q_2^2 when q_2 is sufficiently small. Obviously, $G^c(q \mid p^c, p^{nc}, \delta) \geq h(\underline{u} + D(q))$. Also,

$$G^c(q \mid p^c, p^{nc}, \delta) \leq h(v_H)(1-(1-q)(1-\bar{p})) + h(v_L)(1-q)(1-\bar{p}),$$

where $\bar{p} = \delta p^c + (1-\delta)p^{nc}$, $v_H = \underline{u} + D(q) + D'(q)/[1-\bar{p}]$, $v_L = \underline{u} + D(q) - D'(q)[1-(1-\bar{p})(1-q)]/[1-\bar{p}]$. Substituting for v_H and v_L and using Taylor series expansion around $\underline{u} + D(q)$ we obtain

$$\begin{aligned} G^c(q \mid p^c, p^{nc}, \delta) \leq\ & h(\underline{u} + D(q)) + h'(\underline{u} + D(q) + \beta_1)\frac{(1-(1-q)(1-\bar{p}))D'(q)^2(1-q)^2}{2} \\ & + h'(\underline{u} + D(q) + \beta_2)\frac{(1-\bar{p})(1-q)D'(q)^2\left(\frac{1}{1-\bar{p}} - (1-q)\right)^2}{2}, \end{aligned}$$

where $\beta_1 \in [0, D'(q)(1-q)]$, $\beta_2 \in [0, D'(q)\frac{1-(1-\bar{p})(1-q)}{1-\bar{p}}]$. Using this inequality and invoking the convexity of $D(\cdot)$, we have

$$G^c(q_2 \mid p^c, p^{nc}, \delta) - G^c(q_1 \mid p^c, p^{nc}, \delta)$$
$$\leq h'(\underline{u} + D(q_2))D'(q_2)\frac{q_2}{2} + h''(\underline{u} + D(q_2) + \beta_1)\frac{(1-(1-q_2)(1-\bar{p}))D'(q_2)^2(1-q_2)^2}{2}$$
$$- h''(\underline{u} + D(q_2) + \beta_2)\frac{(1-\bar{p})(1-q)D'(q_2)^2\left(\frac{1}{1-\bar{p}} - (1-q_2)\right)^2}{2}.$$

Since $D'(0) = 0$, $D''(0) < \infty$ and $h'(\underline{u}) < \infty$, we conclude that the above expression is of order q_2^2.

Claim 3. $\exists\, \underline{q}^{nc} > 0$ s.t. $\forall\, q \in [0, \underline{q}^{nc}]$, $\delta \in [0, 1]$ and $p^c, p^{nc} \in [0, p^{\max}]$

$$V^{nc}(2\underline{q}^{nc} \mid p^c, p^{nc}, \delta) > V^{nc}(q \mid p^c, p^{nc}, \sigma).$$

Proof of this claim follows the same steps as the proof of claim 2 and is therefore omitted.

Claim 4. Let $p^{\min} = \min\{\underline{q}^c, \underline{q}^{nc}\}$. If effort p is taken with a positive probability in some equilibrium, then $p \in [p^{\min}, p^{\max}]$. This claim is a simple consequence of claims 1, 2, 3.

Claim 5. $\exists\, \sigma_1 > 0$ and $d > 0$ s.t. $G^{nc}(p \mid q^c, q^{nc}, \sigma) - G^c(p \mid q^c, q^{nc}, \sigma) > d\ \forall\, \sigma \leq \sigma_1$, $p \leq p^{\max}$, and $q^c, q^{nc} \in [p^{\min}, p^{\max}]$. It is easy to show that $\forall\, p \leq p^{\max}$, $q^c, q^{nc} \in [p^{\min}, p^{\max}]$:

(i) $G^{nc}(p \mid q^c, q^{nc}, 0) - G^c(p \mid q^c, q^{nc}, 0) = k > 0$.

(ii) $\exists\, \sigma_1 > 0$ and $b > 0$ s.t. $G^{nc}(p \mid q^c, q^{nc}, \sigma) - G^c(p \mid q^c, q^{nc}, \sigma) > b\ \forall\, \sigma \in (0, \sigma_1)$.

Statement (i) is true because collusion constraint (A16) in Problem $CC(p \mid q^c, q^{nc}, 0)$ is nonbinding, and so Problem $CC(p \mid q^c, q^{nc}, 0)$ is equivalent to Problem $NC(p \mid q^c, q^{nc}, 0)$ without corresponding no-collusion constraint (A7). Presence of binding no-collusion constraint (A7) implies that $G^{nc}(p \mid q^c, q^{nc}, 0) > G^c(p \mid q^c, q^{nc}, 0)$.

Statement (ii) holds because $G^c(p \mid q^c, q^{nc}, \sigma)$ is continuous in σ everywhere, and no-collusion constraint (A6) in Problem $NC(p \mid q^c, q^{nc}, \sigma)$ is binding. To establish the claim, let $d = \min\{k, b\}$.

Claim 6. Let $R^{nc}(p \mid q^c, q^{nc}, \sigma)$ ($R^{cc}(p \mid q^c, q^{nc}, \sigma)$) be the revenue that a firm gets when it offers incentive scheme $NC(p \mid q^c, q^{nc}, \sigma)$ ($CC(p \mid q^c, q^{nc}, \sigma)$). Then $\exists\, \sigma_2 > 0$ s.t. $\mid R^{nc}(p \mid q^c, q^{nc}, \sigma) - R^{cc}(p \mid q^c, q^{nc}, \sigma) \mid < d/2$ $\forall\, \sigma \leq \sigma_2$.

This claim follows by inspection.

Claim 7. Let $\underline{\sigma} = \min\{\sigma_1, \sigma_2\}$. Then $V^{nc}(p \mid q^{nc}, q^c, \sigma) < V^c(p \mid q^{nc}, q^c, \sigma)\ \forall\, \sigma < \underline{\sigma}$, $p \leq p^{\max}$, $q^{nc}, q^c \in [p^{\min}, p^{\max}]$. This claim follows from claims 5 and 6 and completes the proof of the lemma. *Q.E.D.*

By Lemmas 2 and 3, $W_A(\cdot)$ ($W_B(\cdot)$) is continuous everywhere except at $\sigma = 0$ ($\delta = 0$). Then by Berge's Maximum theorem, the best-response correspondences $BR^A : (q^{nc}, q^c, \sigma) \longrightarrow (p^{nc}, p^c, \delta)$ and $BR^B : (p^{nc}, p^c, \delta) \longrightarrow (q^{nc}, q^c, \sigma)$ in game M are upper hemicontinuous except possibly around $\sigma = 0$ and $\delta = 0$.

To establish the upper hemicontinuity at $\sigma = 0$ ($\delta = 0$), note that by (i) of Lemma A1 we can restrict the domain of the best-response correspondence $BR^A(q^{nc}, q^c, \sigma)$ ($BR^B(p^{nc}, p^c, \delta)$) to $[p^{\min}, p^{\max}]^2 \times [0, 1]$. The image of $BR^A(q^{nc}, q^c, \sigma)$ ($BR^B(p^{nc}, p^c, \delta)$) on this domain is also contained in $[p^{\min}, p^{\max}]^2 \times [0, 1]$. By part (ii) of Lemma A1, on this domain the projection $BR^A_\delta(q^{nc}, q^c, \sigma)$ on δ ($BR^B_\sigma(p^{nc}, p^c, \delta)$ on σ) is equal to one when $\sigma < \bar{\sigma}$ (when $\delta < \bar{\sigma}$), which implies that $BR^A_{p^{nc}}(q^{nc}, q^c, \sigma) = [0, 1]$ when $\sigma < \bar{\sigma}$, and $BR^B_{q^{nc}}(p^{nc}, p^c, \delta) = [0, 1]$ when $\delta < \bar{\sigma}$. This establishes that the best-response correspondences are hemicontinuous at $\sigma = 0$ and $\delta = 0$ on the relevant domain. Therefore, by Kakutani's fixed-point theorem, an equilibrium in game M exists. *Q.E.D.*

Proof of Proposition 1. Suppose that there exists an equilibrium where information exchange occurs with probability 1. Let p^* be the highest effort in the supports of the distributions of efforts chosen by the two employees in this equilibrium. Without loss of generality, assume that p^* is in the support of the distribution chosen by employee A. Let $\bar{q}$ denote employee B's expected effort. Obviously, $p^* \geq \bar{q}$. Then incentive scheme v_{ij} ($i, j \in \{1, 2\}$) used by firm A to induce p^* must satisfy the following incentive constraint: $(v_{22} - v_{11})(1 - \bar{q}) = D'(p^*)$.

Let us demonstrate that firm A can deviate profitably by preventing information exchange. Suppose it offers incentive scheme w_{ij} s.t. $w_{21} = w_{22} = w_{12} = v_{22}$, $w_{11} = v_{11}$. Then employee A will refuse to exchange information but will take the same effort p^*, since

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

Clearly, firm A incurs the same expected cost by offering either incentive scheme w_{ij} or incentive scheme v_{ij}. However, since $\pi_{21} - \pi_{22} > \pi_{22} - \pi_{12}$ and $p^* \geq \bar{q}$, offering w_{ij} instead of v_{ij} increases the expected revenue by

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

The inequality is nonstrict only if $p^* = q$ and $R = 1$. To establish the result in this case, note that incentive scheme w_{ij} is suboptimal, and that firm A can prevent exchange of information at a lower cost by offering a different incentive scheme. *Q.E.D.*

Proof of Proposition 2. Suppose that firm A(B) can offer only incentive schemes of type *NC* (*CC*). It is easy to show that an equilibrium exists in this game. Let us fix any such equilibrium, and show that it is also an equilibrium of the original game. Clearly, firm B has no incentive to deviate. Its strategy is optimal in the class *CC* by construction, while deviating to an incentive scheme of class *NC* will only increase its cost. Let $\bar{q}$ be employee B's expected effort in this equilibrium. Then $\bar{q} < \overline{p}$, where $\overline{p} < 1$ is s.t. $D'(\overline{p}) = \overline{K}$.

If firm A deviates from the candidate equilibrium and offers incentive scheme v_{ij} $(i, j \in \{1, 2\})$ of class *CC*, then information exchange occurs with probability 1 and employee A takes effort p^c satisfying $(v_{22} - v_{11})\bar{q} = D'(p^c)$. When such v_{ij} is chosen optimally, $p^c \geq \underline{p}$, where $\underline{p} > 0$ solves

$$h(\hat{v}_{22}) - h(\hat{v}_{11}) + \left(h'(\hat{v}_{22}) - h'(\hat{v}_{11})\right) \frac{1 - \underline{p}}{1 - \overline{p}} \left(1 - (1 - \underline{p})(1 - \overline{p})\right) = \underline{K}$$

where $\hat{v}_{22} = \underline{u} + D(\underline{p}) + D'(\underline{p})(1 - \underline{p})$ and $\hat{v}_{11} = \underline{u} + D(\underline{p}) - D'(\underline{p})\{[1 - (1 - \underline{p})(1 - \overline{p})]/[1 - \overline{p}]\}$.

Let $k = (1 - \underline{p})\overline{p}/\underline{p}(1 - \overline{p})$. Suppose that, instead of v_{ij}, firm A offers incentive scheme w_{ij} $(i, j \in \{1, 2\})$ s.t. $w_{21} = w_{22} = w_{12} = v_{22}$ and $w_{11} = v_{11}$. Then employee A will take effort p^c and refuse to exchange information. Therefore, firm A incurs the same expected cost by offering v_{ij} or w_{ij}. Firm A's expected revenues from w_{ij} and v_{ij} differ by

$$(\pi_{21} - \pi_{22})p^c(1 - \bar{q}) + (\pi_{12} - \pi_{22})(1 - p^c)\bar{q} \geq (\pi_{21} - \pi_{22})\underline{p}(1 - \overline{p}) + (\pi_{12} - \pi_{22})(1 - \underline{p})\overline{p} > 0.$$

The second inequality holds because $R > k$. This establishes that firm A cannot increase its profits by using an incentive scheme of class *CC*. *Q.E.D.*

Proof of Proposition 3. Established by modifying the proof of Proposition 2. *Q.E.D.*

Proof of Proposition 5. Consider the case $\kappa_I = 0$, i.e., $\pi_{21} = \pi_{22} \equiv \pi_H > \pi_{12} = \pi_{11} \equiv \pi_L$. First let us establish that there are no equilibria where information exchange takes place with probability less than 1. Fix an arbitrary strategy (q^c, q^{nc}, σ) of employee B. If firm A induces its employee to take effort p and refuse to exchange information, then its expected revenue is equal to $\pi_H p + \pi_L(1 - p)$ and its expected cost is at least $h(v_H)p + h(v_L)(1 - p)$, where $v_H = \underline{u} + D(p) + (1 - p)D'(p)$ and $v_L = \underline{u} + D(p) - pD'(p)$.

Now suppose that firm A modifies its strategy and induces its employee to agree to exchange information and take effort p' s.t. $p' + (1 - p')\sigma q^c = p$. Then firm A's revenue $\pi_H(p' + (1 - p')\sigma q^c) + \pi_L(1 - p')(1 - \sigma q^c)$ is the same as originally. Its expected cost is at most $h(v'_H)(p' + (1 - p')\sigma q^c) + h(v'_L)(1 - p')(1 - \sigma q^c)$, where $v'_H = \underline{u} + D(p') + (1 - p')D'(p')$ and $v'_L = \underline{u} + D(p') - [p' + \sigma^c_q/(1 - \sigma^c_q)]D'(p')$. Since $p' \leq p$, the expected payment to the employee has decreased. Since $D(x) + (1 - x)D'(x)$ is increasing in x, we have $v'_H \leq v_H$. Then convexity of $h(\cdot)$ implies that firm A's expected cost decreases as a result of this modification. Thus, we have shown that it is optimal for firm A to induce its employee to agree to exchange information, because it can obtain the same revenue at a lower cost.

To establish existence of an equilibrium, consider a game in which both firms can only offer incentive schemes of class *CC*. Existence of an equilibrium in this game follows by standard arguments. Compactness of the action space and the regularity conditions imposed on $h(\cdot)$ and $D(\cdot)$ guarantee that there is a finite number of such equilibria. The previous argument implies that these equilibria are preserved when the firms can also offer incentive schemes of class *NC*.

Inspecting the proof, it is easy to see that the result holds by continuity for sufficiently small positive κ_I. *Q.E.D*

□ **Derivation of the cost functions in the limited-liability case.** To show that $G^{nc}(p \mid q^c, q^{nc}, \sigma) \geq D'(p)p$, combine the limited-liability constraints $v_{12} \geq 0$ and $v_{11} \geq 0$ with the incentive constraint $(v_{21} - v_{11})(1 - \bar{q}) + (v_{22} - v_{12})\bar{q} = D'(p)$. This lower bound is tight and is achieved by setting $v_{12} = v_{11} = 0$ and choosing $v_{21} > v_{22}$ in such a way that the appropriate no-collusion constraint (A6) or (A7) holds. Similarly, we can show that $G^c(p \mid q^c, q^{nc}, 0) = D'(p)p$.

To compute $G^c(p \mid q^c, q^{nc}, \sigma)$, note that the incentive constraint (A17) and the collusion constraint (A16) imply that it is optimal to set $v_{12} = 0$ and $v_{11} = 0$. Then using the incentive constraint (A17) we obtain $G^c(p \mid q^c, q^{nc}, \sigma) = D'(p)p + \sigma q^c v_{22}$. Finally, the bounds on v_{22} follow from the collusion constraint (A16). Note that $v_{22} = D'(p)/(1 - q^c)$ when $\sigma = 1$.

Proof of Proposition 6. Consider the following sufficient condition for the existence of a cooperative equilibrium: $U^c(p^d, p^c) \geq U^{nc}(p^d, p^c)$. Rewriting it explicitly and using $D'(p) \leq pD''(p)$, $\pi_{22} > \pi_{11}$, and (3), we obtain that this sufficient condition holds if the following inequality is true:

$$(\pi_{22} - \pi_{12})\, p^c \left(1 - p^d - \frac{p^c}{2(1-p^c)}\right) \geq (\pi_{21} - \pi_{11}) \left(p^d(1-p^c) + \frac{p^c}{2}\right). \tag{A26}$$

If K is sufficiently small, then p^d and p^c are small enough that $1 - p^d - p^c/2(1-p^c) = \mu$ for some $\mu \in (0, 1)$. In this case, $p^c < 1/2$ because $p^d \geq p^c$. Then conditions (ii) and (iii) imply that $(\pi_{22} - \pi_{11})(1-p^c)/[(\pi_{21} - \pi_{11})(1-p^c) + (\pi_{22} - \pi_{12})p^c] > rb/(1+b)$. From this inequality, (2), and (3), it follows that $\exists\, \zeta > 0$ s.t. $p^c \geq \zeta p^d$ and ζ is weakly increasing in b and r. Therefore, (A26) holds if $(\pi_{22} - \pi_{12})\mu\zeta \geq (3/2)(\pi_{21} - \pi_{11})$. The last inequality holds when b is sufficiently large. *Q.E.D.*

Proof of Proposition 7. (i) The cooperative equilibrium exists if $U^c(p^d, p^c) \geq U^{nc}(p^d, p^c)$. Using $D'(p) \leq pD''(p)$, this condition can be rewritten as $(1-p^d)(1-p^c) > 1/2$, which holds when p^c and p^d are small enough, or equivalently, $\pi_H - \pi_L$ is sufficiently small.

(ii) Cooperative equilibrium fails to exist if

$$U^c(p^c, p^c) - U^{nc}(p^c + p^c(1-p^c), p^c) = -\left(p^c + p^c(1-p^c)\right)\left(\frac{D'(p^c)}{1-p^c} - D'(p^c + p^c(1-p^c))\right) < 0.$$

The expression in the large brackets is positive if and only if $\int_{p^c}^{p^c+p^c(1-p^c)} D''(x)dx \leq p^c D'(p^c + p^c(1-p^c))$. Since $D'''(p) \geq 0$, this inequality holds if $(1-p)D''(p + p(1-p)) \leq D'(p + p(1-p))$ or $(1-q)^{1/2}D''(q) \leq D'(q)$, where $q = p + p(1-p)$. If $D(\cdot)$ satisfies the condition stated in the proposition, $\exists\, \tilde{q} \in (0, 1)$ s.t. the last inequality holds if $p + p(1-p) \geq \tilde{q}$. Obviously, $p^c + p^c(1-p^c) \geq \tilde{q}$ if and only if $\pi_H - \pi_L$ is large enough. *Q.E.D.*

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[Footnotes]

[5] **An Analysis of the Principal-Agent Problem**
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