Information leakage in innovation outsourcing

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This paper studies an R&D outsourcing contract between a firm and a contractor, considering the possibility that in the interim stage, the contractor might sell the innovation to a rival firm. Our result points out that due to the competition in the interim stage, the reward needed to prevent leakage will be pushed up to the extent that a profitable leakage-free contract does not exist. This result will also apply to cases considering revenue-sharing schemes and a disclosure punishment for commercial theft. Then, we demonstrate that in a competitive mechanism where the R&D firm hires two contractors together with a relative performance scheme, the disclosure punishment might help and there exists a perfect Bayesian Nash equilibrium where the probability of information leakage is lower and the equilibrium reward is also cheaper than hiring one contractor.

1. Introduction

Outsourcing has become an important business strategy in a global economy (see, e.g., Grossman and Helpman, 2005). Firms subcontract a wide range of activities, ranging from product design to assembly, from research and development to marketing, distribution and after-sales service. Among the various reasons,[1] 'cost reduction' has been considered the main driving factor for outsourcing. In particular, R&D outsourcing can reduce time and money expenditures, free up resources for other endeavors and reduce technical uncertainty. McKinsey and Company (2003) reported that the reduction of labor costs results in savings of at least 45–55%. Every dollar of labor cost moved offshore creates US$ 1.45–1.47 globally, US$ 1.12–1.14 to the United States, and 33 cents to the hosting country. They concluded that R&D outsourcing is a 'win–win' proposition for both companies and workers overseas.

However, since R&D activities are linked directly to a company's core secrets concerning new technology or new product, protection of intellectual property has been the most crucial issue in R&D outsourcing (Balachandra, 2005). Although governments[2] in the outsourcing countries have been taking steps and enacting laws to assure firms that intellectual property is protected, effective enforcement of laws requires that the owner of this information must have taken reasonable measures to safeguard it from unauthorized disclosure. Writing a non-disclosure agreement or contract will be the first step for protecting intellectual property. Hence, there has been a growing interest on R&D outsourcing contracts with particular focus on information disclosure or leakage (see, e.g., Lai et al., 2006; Qiu, 2006). In this paper, we will follow this line of research, and study an R&D outsourcing contract considering the possibility that the contractor might deliberately[3] sell the innovation to the rivals. We will present the problem caused by deliberate information leakage, and propose a leakage free mechanism for the R&D firm.

The first step to modelling an R&D contract is to identify the key difference between R&D activities and the others. According to Reinganum (1989), innovation is featured by its uncertainty in both the timing and probability of success. This indicates that R&D activities are normally time consuming and involve a high risk of failure. Moreover, due to the uncertainty of innovation, the contractor will become better informed of the status of R&D activities, and this gives the contractor an opportunity to manipulate the information; that is, the contractor can possibly sell the innovation to the rivals without being detected.[4] The closest literature to this process of information leakage is that on contract renegotiation (e.g., Fudenberg and Tirole, 1990) or collusion. The contract renegotiation literature addresses the possibility that the contractor might propose to renegotiate the deals of contract in the interim stage; the collusion literature addresses the situation where the contractor might collude with the monitor in a multiple-layer hierarchy environment (see more discussion in section 1.1). The major difference[5] of our setting is: the leakage problem is indeed a form of renegotiation or collusion, but it is with the rival of the R&D firm. Proposing to sell the information to a rival will create a price competition between the original contract reward and the new offer by the rival; the rival firm will outbid the original reward as long as there is benefit from having the innovation, and this will push up the level of original reward needed to prevent the rival from making a successful offer. As a consequence, the R&D firm needs to pay a reward that is at least higher than its own benefit from the innovation, to prevent successful leakage. In other words, a leakage-free[6] R&D contract does not exist in a symmetric[7] setting.

The reason for the nonexistence of a leakage-free contract is because in a direct mechanism, the contractor is implicitly given more bargaining power (i.e., by selling the innovation without being detected). Both the R&D firm and the rival will compete for the only contractor's loyalty, and so the reward is pushed up due to competition. If some competition can be introduced to the contractor side, then the R&D firm's bargaining power will be increased and it will not necessarily pay the contractor the highest benefit in order to prevent leakage. However, according to Holmstrom (1982), 'forcing agents to compete with each other is valueless if there is no common underlying uncertainty,' and the keypoint for information extraction is to 'create information systems that separate out individual contributions.' Hence, in the second part of this paper, we will demonstrate how a competitive mechanism, where the R&D firm hires two contractors and introduces a relative performance regime (see Holmstrom and Milgrom, 1991), can overcome the over-rewarding problem from information leakage.

Overall, we will study an R&D outsourcing contract between a firm and a contractor, considering the possibility that in the interim stage, the contractor might sell the innovation to a rival firm. Our result points out that due to the competition in the interim stage, a profitable leakage-free contract does not exist. This result will apply to cases considering revenue-sharing schemes (Lai et al., 2006) and disclosure punishments for commercial theft (see, e.g., Section 1832 of the *Economic Espionage Act*; Graetz et al., 1986). Then, we demonstrate that in a competitive mechanism where the R&D firm hires two contractors together with a relative performance scheme, the disclosure punishment might help and there exists a perfect Bayesian Nash equilibrium, where the probability of information leakage is lower and the equilibrium reward is also cheaper than hiring one contractor.

1.1. Related literature

Our paper is related to three lines of research: R&D outsourcing contracts, contracting with collusion, and contracting with multiple agents. The first line of research deals with the same topic as our paper but uses a different model setup; the second line uses a similar model setup but we will point out the difference from our model and discuss the consequence from such a difference; and the third addresses the benefit from hiring multiple agents, as we will suggest in Section 3.

Firstly, although there have been many theoretical discussions on the effects of R&D activities and innovation imitation in an open or closed economy (see, e.g., Dinopoulos and Segerstrom, 2006, for recent literature), only a few of them address particularly on R&D outsourcing contracts (see Lai et al., 2006; Qiu, 2006). Following the pioneering outsourcing paper by Grossman and Helpman (2005), all these papers analyze firms' in-house/outsourcing decisions in a general equilibrium framework. This is different from our partial analysis setting, and we provide the reasoning as follows. The advantage for using a general equilibrium framework is the convenience to understand the overall effect of R&D outsourcing. However, because the economy system is so complicated, some simplifications are needed to make the model tractable, but these simplifications can sometimes omit critical features of R&D outsourcing. For example, Lai et al. (2006) consider the leakage problem by assuming that leakage will reduce the R&D firm's market share, but with symmetric information, it is difficult to describe in more details how the information is leaked to a rival firm. Moreover, due to the assumption of perfect information, it is possible to find a subgame perfect equilibrium where the leakage problem can be prevented by precommitting to a reward that the contractor do not sell the innovation. Such a reward, as we will demonstrate, does not exist in an asymmetric information contract.

In sum, our paper follows most contract literature in considering a partial analysis framework. Apart from the difference in information structure, there are some similarities between our paper and the existing works. Lai et al. (2006) emphasize how the choice of rewarding scheme (i.e., fixed or revenue-sharing) will affect the contractor's leakage decision. Our paper, differently, demonstrates that the leakage problem under asymmetric information cannot be prevented by either fixed or revenue-sharing schemes. The reason is because the incentive for cheating is the same under both schemes and hence, the over-rewarding problem still exists with the revenue-sharing scheme. The form of rewarding schemes make no difference to the result. Qiu (2006) studies firms' in-house/outsourcing decisions by considering different degrees of contract enforcement, which corresponds to the power of copyright protection. Qiu concludes that when copyright protection is weak, only customized software will be developed; when copyright protection is strong, both customized software and packaged software will be developed. Our paper is related to Qiu's model in addressing the effect of a pecuniary punishment for information leakage. However, with the same reasoning of bargaining power and innovation uncertainty as described above, the device of a pecuniary punishment cannot prevent the leakage problem in a single contractor case. We will demonstrate that this device might work in a competitive mechanism in Section 3.

Secondly, our model setup is similar to the theory of contract with collusion. This line of research[8] considers contracting in a multiple-layer hierarchy environment, e.g., the government, a monitor, and a regulated firm, where the monitor and the regulated firm might collude and take action against the government. The main difference of our model is that the leakage problem is actually a form of collusion with the rival of the R&D firm. Because the rival firm has an incentive to compete with the R&D firm by means of making counter-offers, a collusion-proof contract does not exist in our model. However, it is worthwhile to discuss whether it is without loss of generality to focus on a collusion-proof contract. We will demonstrate shortly that a partial collusion cannot happen in equilibrium.

Moreover, as described, the closest literature to the process of information leakage is that on contract renegotiation (e.g., Fudenberg and Tirole, 1990). The major difference of our setting is that the leakage problem is indeed a form of renegotiation or collusion, but it is with the rival of the R&D firm. Proposing to sell the information to the rival will create a price competition between the original contract reward and the new offer by the rival; the rival firm will outbid the original reward as long as there is benefit from having the innovation, and this will push up the level of original reward needed to prevent the rival from making a successful offer. As a consequence, the R&D firm needs to pay a reward that is at least higher than its own benefit from the innovation, to prevent successful leakage. In other words, a leakage-free R&D contract does not exist in a symmetric setting.

Finally, our main result asserts that when the R&D firm hires two contractors together with a relative performance scheme, the leakage problem can be mitigated and the equilibrium reward is also cheaper (see also Ho, 2008). Dewatripont and Tirole (1999) consider whether to hire one or two agents to investigate two causes. They conclude that competition between the two agents will allow the organization either to obtain more information or to obtain the information at a lower cost. The reason behind this is: if hiring only one agent, there will be a rent for the agent to put in the second effort (for the second cause); but 'with two agents, it is easy to leave them no rents by giving each a positive wage only if he succeeds in moving policy away from the status quo' (p. 14). Our model is different in addressing that leakage is collusion with an outside party of an opposite preference. Moreover, a competitive mechanism is cheaper in our model because with two contractors, there is more chance that a betrayer can be identified and can receive the disclosure punishment (see Section 3 for details).

The organization for the rest of the paper is as follows: Section 2 describes the environment of a duopoly market with two identical firms. One of the two firms decides to engage in R&D outsourcing before production. We will explain the leakage problem in the contracting process, and demonstrate the nonexistence of a leakage-free contract. Section 3 presents the competitive mechanism and characterizes a perfect Bayesian Nash equilibrium where both the chance of information leakage and the equilibrium reward are lower than hiring one contractor. The last section contains the concluding remarks.

2. The model

This section describes a duopoly market with two firms: firm 1 and 2. Before production, firm 1 decides to engage in R&D outsourcing on a process innovation with an external contractor or research unit. To focus on the information leakage problem and looking for a solution for this problem, we will eschew the discussion on R&D firm's in-house/outsourcing[9] decision, by assuming directly that firm 1 will undertake the R&D outsourcing. Also, we assume only one R&D firm to avoid the strategic correlation problem in a common[10]agency model.

The environment: We will consider a production market with two firms, each producing a homogenous product denoted by q_i, $i = 1,2$. The market demand is described by a downward sloping linear function, with a sufficient large scale: $P = a - b(q_1 + q_2)$ with $0 < q_1 + q_2 < a$. To simplify, it is assumed that before engaging in R&D activities, all firms are equipped with the same production technology, which is described by a linear production cost function: cq_i with $c > 0$. The production cost refers to all expenditure used for production, such as machine costs, capital cost, and labor salaries (such as the cost of innovation, R&D, and knowledge management). Our paper will consider a process innovation, which can be a new machine or a management system to cut the cost.

Now assume that, before production, firm 1 decides to hire an external contractor (denoted by 0) to perform a research on a cost-reducing (i.e., process) innovation. The innovation is uncertain and the probability of success will depend on the contractor's effort in R&D. The details and further notations will be given shortly. If the innovation is successful, the production cost will be reduced to $\hat{c}$ $(< c)$. Hence, let c_i denote firm i's production cost, and let $\pi_i(c_i, c_j)$ be firm i's profit associated with cost[11] combination (c_i, c_j) for $i, j = 1,2$, and

$$\pi_i(c_i, c_j) \equiv \max_{q_i}[a - bq_1 - bq_2 - c_i]q_i \qquad (1)$$

The maximization problem is well defined, as equation (1) is differentiable to the second order and concave. The calculation for equilibrium outputs is standard and hence will be omitted. The equilibrium outputs and profits are $q_i = \frac{1}{3b}(a - 2c_i + c_j)$, and $\pi_i(c_i, c_j) = \frac{1}{9b}(a - 2c_i + c_j)^2$, respectively. For firm 1 to engage in the R&D project in the first place, we will assume[12] that $(c - \hat{c})$ is sufficiently large. The following remark provides comparisons on $\pi_i(c_i, c_j)$ for further usage. It says that the gain from having the innovation is greater when the rival firm has a smaller cost difference.

Remark 1. *Let $E_s c_2$ and $E_n c_2$ be two arbitrary costs such that $\hat{c} \le E_s c_2 < E_n c_2 < c$. Then, we have $[\pi_1(\hat{c}, E_s c_2) - \pi_1(c, E_n c_2)] < [\pi_2(c, \hat{c}) - \pi_2(\hat{c}, c)]$.*

Remark 1 is an immediate result from the symmetric setting. We will later demonstrate that if the two firms are not symmetric, the following discussion on information leakage will still apply, but whether there exists a profitable leakage-free contract will depend on whether firm 1 has a higher benefit from innovation. The contracting process is depicted in Figure 1.

Timing: We will assume that firm 1 offers an R&D contract, denoted by C, to the contractor on a *take-it-or-leave-it* basis. The contract contains rewards for different results of innovation, that is, $C \equiv \{\varpi(r), r \in \Theta\}$, where $\varpi(r)$ is the end of contract reward for the reported result r. Notice that this reported result can be different from the true status (to be defined shortly) and the actual values of $\varpi(r)$ will be determined in the equilibrium.

If C is accepted by the contractor, then he needs to make a binary effort decision $e \in E$, with $E = \{0, \bar{e}\}$ which is unobservable to firm 1. The binary efforts are assumed in order to emphasize the leakage problem and to simplify the analysis. For other assumptions of discrete efforts, we need to make more assumptions about the existence of an optimal effort level, and about the relative sizes of expectation that the client might have. The innovation is uncertain and the probability of success depends on exogenous

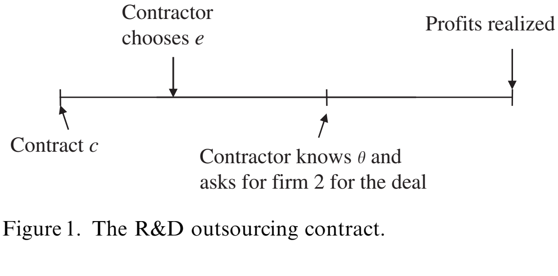

Figure 1. The R&D outsourcing contract.

technical restriction and the contractor's endogenous effort decision on R&D. That is, denote the status[13] of innovation by θ with $\theta \in \Theta = \{s, n\}$. s means that the innovation is successful and the production cost will be reduced to $\hat{c}$ (which is less than c) and n means that the innovation is failed and hence the production cost remains c. There is a prior probability ρ that $\theta = s$ and $(1-\rho)$ that $\theta = n$, where $0 < \rho < 1$ reflects the uncertainty caused by the exogenous technical restriction on innovation. In addition, the probability of success is also affected by the contractor's endogenous effort choice. That is, let $\gamma(s|e)$ denote the effort-dependent probability of success, we will assume that $\gamma(s|0) = 0$ and $\gamma(s|\bar{e}) > 0$. The interpretation of this assumption is: if no effort has been put in, then the probability[14] for a successful innovation is zero; if the full effort has been put in, there is still a chance $\gamma(n|\bar{e})$, which is equal to $1 - \gamma(s|\bar{e})$, that the R&D effort is failed. Finally, putting in effort is costly and the cost is captured by an increasing function $\psi(e)$, with $\psi(0) < \psi(\bar{e})$, and we assume that $\psi(0) = 0$.

After knowing the status of innovation (dented as the *interim stage*) and if the state is s, the contractor might consider to sell the innovation[15] to the rival firm 2 for a second deal.[16] Denote L as the offer made by firm 2 to exchange for the innovation, and this again will be determined in the equilibrium. Let $I(L, \theta)$ denote the contractor's leakage decision on whether to accept the offer, depending on the size of firm 2's offer as well as the status of truth. That is, if $\theta = n$, then we will assume that the contractor cannot fabricate the innovation and hence $I(L, n) = 0$ for all L. If $\theta = s$ and L is high enough, then $I(L, s) = 1$ and he will sell[17] the innovation to firm 2 and report to firm 1 that R&D has failed. If $\theta = s$ but L is not sufficiently high, then $I(L, s) = 0$ and the true status will be reported to firm 1, whose production cost will be reduced to $\hat{c}$.

Notice that because the innovation is uncertain, the contractor is the only one who knows the status of innovation. Firm 1 cannot distinguish the following three cases: (i) no effort has been put in; (ii) the effort has failed; (iii) the innovation has been sold. Hence, although firm 1 might be suspecting that there is such a deal going on, it cannot counteract firm 2 in this deal. However, anticipating information leakage to happen, firm 1 cannot just pretend to be ignorant. A more realistic assumption will be for firm 1 to include in the clauses of the contract a punishment for this kind of deliberate disclosure of commercial secrets. The empirical support for this assumption is Section 1832 of the Economic Espionage Act 1996. Section 1832 renders commercial theft of trade secrets a criminal act regardless of who benefits (foreigners or non-foreigners). A defendant convicted for theft of trade secrets under Section 1832 can be imprisoned for up to 10 years and fined \$500,000 or both. Corporations and other entities can be fined no more than \$5 million. To simplify, we will assume[18] a pecuniary punishment D for a convicted contractor. By '*convicted*,' we refer to the case where firm 1 is *100% certain that the innovation has been sold*. We will discuss the effect of this punishment at the end of Section 2 and Section 3 in more detail.

Finally, according to the contractor's report, firm 1's production cost is denoted by $c_1(r)$, which is c for $r = n$ and $\hat{c}$ for $r = s$. However, due to the secret deal between the informed contractor and firm 2, the production has become an *incomplete information* game. That is, firm 2 of course knows whether it has successfully bought the innovation and hence, it knows c_2 surely; that is, $c_2 = I(L, \theta)\hat{c} + (1 - I(L, \theta))c$. Given $\theta = s$, if L is accepted, then firm 2's cost is $\hat{c}$; otherwise, its cost is c. Firm 1, on the other hand, needs to guess firm 2's cost depending on whether firm 1 believes that the contractor has been cheating. Denote $\sigma(r)$ as the probability that firm 1 thinks that firm 2 has cost $\hat{c}$, and this belief will be derived shortly according[19] to the Bayes' rule. Then firm 1's expectation about firm 2's cost is denoted by $E_r c_2$, which is given by $\sigma(r)\hat{c} + (1 - \sigma(r))c$.

Hence, firm 1 and firm 2's realized profits are given by

$$\pi_1(c_1(r), E_r c_2) - \varpi(r) \text{ and } \pi_2(c_1(r), c_2) - I(L, \theta)L \tag{2}$$

for $\theta = s, n$, respectively. The interpretations for the two formulations are: Given a report r, firm 1's production cost will be $c_1(r)$ and it can rationally calculate the chance that the innovation has been sold to firm 2 (i.e., $\sigma(r)$), and hence anticipate that firm 2's production cost to be $E_r c_2$. $\varpi(r)$ is the reward paid to the contractor for reporting r. On the other hand, firm 2 knows for sure its production cost, which is either c or $\hat{c}$ depending on whether the contractor accepts its offer of L at state θ. Finally, the contractor's realized payoff is

$$(1 - I(L, \theta))\varpi(s) + I(L, \theta)(\varpi(n) + L) - \psi(e), \text{ for } \theta \in \Theta \tag{3}$$

which consists of a reward for reporting r, a benefit from selling the innovation L and the effort cost.

Overall, we consider an R&D contracting process with the possibility of information leakage. This setup fits in most R&D outsourcing contracts in many areas such as pharmacy, ICT, astronautic development, and even basic research in universities. The key feature of R&D activities is that the contractor possesses private information in the interim stage, and this gives the contractor more bargaining power as it can cheat on the employing firm without being identified. We will later show how this will affect the information rent in the leakage-free contract. Notice that our concern is the deliberate information leakage that the contractor sells the private information to the rival firm purposely. This is different from other forms of information leakage, including leakage through publicly observable variables like prices (Grossman and Stiglitz, 1980; Brunnermeier, 2005), actions (Banerjee, 1992; Bikhchandani et al., 1992), and R&D collaboration (Jaffe, 1986; Perez-Castillo and Sandonis, 1996).

Finally, there are some discussions about whether different forms of reward, such as the revenue-sharing scheme, can mitigate the contractor's leakage motivation. It is expected that, by sharing the revenue with the contractor, the R&D firm and the contractor will have more similar preferences and hence the motivation for information leakage can be reduced. Lai et al. (2006) have analyzed the contractor's leakage decision under different levels of revenue sharing. However, our model will demonstrate that the revenue-sharing scheme cannot be leakage free either. The reason is because the incentive for cheating is still the same as the fixed-revenue scheme, and hence the over-rewarding problem still exists under the revenue-sharing scheme (more details later).

2.1. Leakage-free contract

We will follow the revelation principle (see Myerson, 1979) and concentrate on a direct mechanism, where firm 1 designs an incentive compatible rewarding scheme, and the *honest and obedient* contractor will report the status of innovation truthfully. As private information actually emerges in the interim stage as the outcome of innovation, we will follow the literature on contracts with renegotiation or collusion by seeking for a 'leakage free contract.' Because the incentive scheme involves actions in the continuing production game, we will solve *backward* the timing in Figure 1.

Firstly, recall that $\sigma(r)$ is the probability that after receiving report r, firm 1 thinks that the innovation is actually successful but the contractor has sold it to firm 2. We now explain how this is derived by the Bayes' rule. For $r=s$, firm 1 knows that $\theta=s$, and the contractor has put in full effort and has not betrayed (i.e., $I(L,s)=0$). Hence, $\sigma(s)=\rho\gamma(s|e)I(L,s)$, which is equal to 0. On the other hand, for $r=n$, firm 1 cannot distinguish the following three cases: (i) no effort has been put in; (ii) the effort has failed; and (iii) the innovation has been sold. Hence,

$$\sigma(n)=\frac{\rho\gamma(s|e)I(L,s)}{\rho[\gamma(s|e)I(L,s)+(1-\gamma(s|e))]+(1-\rho)} \tag{4}$$

which is smaller than ρ. The denominator is the total probability for reporting n, and the nominator denotes the chance for successful information leakage. Given this belief, the equilibrium outputs under incomplete information[20] are given by equations (1) and (2).

2.1.1. Leakage decision

The contractor's leakage decision will depend on the type as well as firm 2's offer. First, if $\theta=n$, then, as the contractor has nothing to offer, $I(L,n)=0$ for all L. Second, if $\theta=s$, it is assumed that the contractor only cares about the pecuniary[21] revenue; that is, he will sell the innovation to firm 2 iff $L+\varpi(n)\geq\varpi(s)$, where $\varpi(n)$ denotes the reward for reporting n (instead of s). That is, $I(L,s)=1$ if[22] $L\geq\varpi(s)-\varpi(n)$ and $I(L,s)=0$ for otherwise.

Firm 2's decision is to decide whether to outbid firm 1's reward and get the innovation. As the contractor will sell the innovation iff $L\geq\varpi(s)-\varpi(n)$, the minimum bid for information leakage is $L=\varpi(s)-\varpi(n)$. Firm 2 will offer the bid up to a maximal level $\bar{L}$, which is determined by $\pi_2(c_1(n),\hat{c})-\bar{L}=\pi_2(c_1(s),c)$. That is, $\bar{L}$ is the net benefit that firm 2 can get from buying the innovation and changing the contractors' report from s to n. We can summarize firm 2's decision as:

$$\text{to offer } L=\varpi(s)-\varpi(n) \text{ if } L\leq\bar{L} \tag{5}$$

For further usage, we will refer to the following situation as *successful information leakage*: When $\theta=s$, firm 2 offers $L\leq\bar{L}$, the contractor accepts the offer (i.e., $I(L,s)=1$), and changes the report from s to n.

2.1.2. Optimal leakage-free contract

We will combine the discussion of the incentive scheme and the contractor's effort decision. According to the revelation principle, we will restrict to rewards that satisfy individual rationality (IR) and incentive compatibility (IC) constraints. As the effort choice is binary, there is no loss to concentrate on a full effort-rewarding scheme. That is, denote $\Pi_0(e)$ as the contractor's expected payoff for an arbitrary level of e, where

$$\Pi_0(e) = \rho\gamma(s|e)[(1 - I(L,s))\varpi(s) + I(L,s)(\varpi(n) + L)] + [(\rho)(1 - \gamma(s|e)) + (1 - \rho)]\varpi(n) - \psi(e).$$

The interpretation is: there will be a prior belief ρ that the innovation is successful, but there is only a probability $\gamma(e|s)$ that the contractor can discover a successful innovation. Moreover, there still are two possibilities: (i) If the successful innovation is reported truthfully, then the contractor gets $\varpi(s)$; (ii) if the innovation is sold to firm 2, he will get $(\varpi(n) + L)$. Finally, there will be a total probability of $[(\rho)(1 - \gamma(s|e)) + (1 - \rho)]$ that the innovation is failed. Notice that $\Pi_0(0) = \varpi(n)$.

The IR and IC constraints are given by

$$\Pi_0(\bar{e}) \geq 0, \qquad \text{(IR)}$$

$$\Pi_0(\bar{e}) \geq \varpi(n). \qquad \text{(IC)}$$

If we can restrict to non-negative rewards, then IC will imply IR. We will ignore the IR constraint henceforth. In addition, to prevent successful information leakage, an extra 'leakage-free' constraint is also required, i.e.,

$$\varpi(s) - \varpi(n) \geq \pi_2(c_1(n), \hat{c}) - \pi_2(c_1(s), c). \qquad \text{(Leakage free)}$$

This constraint requires the difference of the two rewards to be at least higher than the maximal offer that firm 2 can make.

Let $\Pi_1(\bar{e}, C)$ denote firm 1's expected payoff for committing to contract C, which is given by

$$\Pi_1(\bar{e},C) = \rho\gamma(s|\bar{e})(1 - I(L,s))[\pi_1(c_1(s), E_s c_2) - \varpi(s)] + [\rho\gamma(s|\bar{e})I(L,s) + (\rho)(1 - \gamma(s|\bar{e})) + (1-\rho)] \times [\pi_1(c_1(n), E_n c_2) - \varpi(n)].$$

The first part of the expected payoff says that there is a total probability $\rho\gamma(s|\bar{e})(1 - I(L,s))$ that the contractor discovers a successful innovation and does not sell it to firm 2. In this case, firm 1 will receive a report s, resulting in the cost $c_1(s)$, and have an expectation about firm 2's cost $E_s c_2$. The second part says that there is a total probability $[\rho\gamma(s|\bar{e})I(L,s) + (\rho)(1 - \gamma(s|\bar{e})) + (1 - \rho)]$ that the innovation has either failed or has been sold to firm 2. In this case, firm 1 will receive a report n, resulting in the cost $c_1(n)$, and have an expectation about firm 2's cost $E_n c_2$.

As described, due to incomplete information, firm 1 cannot detect or counteract information leakage in the interim stage. Firm 1 can only seek for an R&D contract that can prevent information leakage ex-ante. The definition is given as follows.

Definition 2. *In a leakage-free contract, firm 1* $\max_C \Pi_1(\bar{e}, C)$ *subject to the IC and the leakage-free constraints.*

It is worthwhile to discuss whether it is without a loss of generality to focus on a leakage-free contract. We now argue that there is no equilibrium allowing partial leakage. Notice first that the probability of partial leakage can be captured by $I(L,s)$ by allowing $0 < I(L,s) < 1$. This indicates that the contractor is indifferent between accepting and rejecting firm 2's offer, but firm 2 can easily break the tie by slightly increasing L. Therefore, partial leakage in our setting cannot happen in equilibrium.

Given the leakage-free constraint, firm 2 cannot outbid in the interim stage and hence, $I(L,s) = 0$. Replace this into $\Pi_0(e)$, and the IC becomes

$$[\varpi(s) - \varpi(n)] \geq \frac{\psi(\bar{e})}{\rho\gamma(s|\bar{e})}.$$

To determine which constraints, IC or leakage-free, will be binding, we need to consider the relative sizes of $\pi_2(c_1(n), \hat{c}) - \pi_2(c_1(s), c)$ and $\frac{\psi(\bar{e})}{\rho\gamma(s|\bar{e})}$ as follows. Recall that the status quo of firm 1 is $\pi_1(c, c)$.

(i) If $\pi_2(c_1(n), \hat{c}) - \pi_2(c_1(s), c) > \frac{\psi(\bar{e})}{\rho\gamma(s|\bar{e})}$, then the information leakage constraint should be binding, that is, $\varpi(s) - \varpi(n) = \pi_2(c_1(n), \hat{c}) - \pi_2(c_1(s), c)$. As there is no further restriction on $\varpi(n)$, the cheapest reward is to set $\varpi(n) = 0$. Hence, $\varpi(s) = \pi_2(c_1(n), \hat{c}) - \pi_2(c_1(s), c)$. However, when we replace $\varpi(n)$ and $\varpi(s)$ into $\Pi_1(\bar{e}, C)$, firm 1's expected payoff becomes

$$\Pi_1(\bar{e}, C) = \pi_1(c, E_n c_2) + \rho\gamma(s|\bar{e})(1 - I(L,s)) \{[\pi_1(\hat{c}, E_s c_2) - \pi_1(c, E_n c_2)] - [\pi_2(c, \hat{c}) - \pi_2(\hat{c}, c)]\}.$$

By the symmetry among two firms, Remark 1 describes that $\pi_1(\hat{c}, E_s c_2) - \pi_1(c, E_n c_2)] < [\pi_2(c, \hat{c}) - \pi_2(\hat{c}, c)]$. This implies that the second term of $\Pi_1(\bar{e}, C)$ is negative. Hence, together with the fact that $\pi_1(c, E_n c_2) < \pi_1(c, c)$, we can conclude that firm 1's expected payoff with the leakage-free constraint is worse off than the status quo $\pi_1(c, c)$.

(ii)If $\pi_2(c_1(n), \hat{c}) - \pi_2(c_1(s), c) < \frac{\psi(\bar{e})}{\rho\gamma(s|\bar{e})}$, then the IC constraint should be binding, that is, $\varpi(s) - \varpi(n) = \frac{\psi(\bar{e})}{\rho\gamma(s|\bar{e})}$. As there is no further restriction on $\varpi(n)$, the cheapest reward is to set $\varpi(n) = 0$. Hence, $\varpi(s) = \frac{\psi(\bar{e})}{\rho\gamma(s|\bar{e})}$. As $\pi_2(c_1(n), \hat{c}) - \pi_2(c_1(s), c)$ has caused an expected payoff less than $\pi_1 = (c, c)$, firm 1's payoff must be worse as $\frac{\psi(\bar{e})}{\rho\gamma(s|\bar{e})} > \pi_2(c_1(n), \hat{c}) - \pi_2(c_1(s), c)$.

Overall, in both cases, firm 1's equilibrium payoff is lower than the status quo $\pi_1 = (c, c)$, and hence, a profitable leakage-free contract does not exist.

Proposition 3. *A profitable leakage-free contract does not exist.*

In order to avoid information leakage, the incentive scheme needs to assign a sufficiently high reward to compete with the offer that firm 2 can make. In the interim stage, firm 1 and firm 2 are actually engaged in a sort of price competition; Firm 2 has the motivation to outbid firm 1's reward to buy the innovation, while firm 1 has to reward high enough so that firm 2 cannot outbid. The result is, hence, similar to that of price competition, that is, one of the two firms will offer its highest benefit associated with the innovation, and the firm with a greater benefit will win. Because the possibility of information leakage will change firm 1's expectation about firm 2's production cost, it turns out that firm 1's highest benefit is less than firm 2, who has private information in the production game. Hence, there exists no profitable leakage-free contract.

Before providing our solution for this leakage problem, it is interesting to see whether a revenue-sharing scheme (see Lai et al., 2006) can work in this case. Our answer, however, is no. The reason is because the incentive for cheating remains the same as in the fixed-revenue scheme. To see this, suppose $\varpi(s) = \alpha(s)\pi_1(c_1(s), E_s c_2)$ and $\varpi(n) = \alpha(n)\pi_1(c_1(n), E_s c_2)$, where $\alpha(r)$ is the *share* of profit for reporting r. Take the case of $\pi_2(c_1(n), \hat{c}) - \pi_2(c_1(s), c) > \frac{\psi(\bar{e})}{\rho\gamma(s|\bar{e})}$ for example. The leakage-free constraint should be binding in this case, and hence we have $\alpha(s)\pi_1(c_1(s), E_s c_2) - \alpha(n)\pi_1(c_1(n), E_s c_2) = \pi_2(c_1(n), \hat{c}) - \pi_2(c_1(s), c)$. As there is no further restriction on $\alpha(n)$, the cheapest share is to set $\alpha(n) = 0$. Therefore, $\alpha(s)\pi_1(c_1(s), E_s c_2) = \pi_2(c_1(n), \hat{c}) - \pi_2(c_1(s), c)$. After replacing $\alpha(n)$ and $\alpha(s)$, into $\Pi_1(\bar{e}, C)$, we will have the same result as the fixed reward: firm 1's expected payoff with the leakage-free constraint is worse than the status quo $\pi_1 = (c, c)$.

Next, it is useful to see whether a disclosure punishment D can prevent the leakage. The punishment is supposed to increase the contractor's cost for cheating. That is, let λ denote the probability that firm 1 is 100% certain that the contractor has sold the innovation. In lawsuits, only convicted defendant will be fined, and hence firm 1 needs to be 100% certain that the innovation has been sold out by the contractor. Considering the punishment, the contractor's leakage decision can be rewritten as

$$\text{to sell if } (1 - \lambda)(L + \varpi(n)) + \lambda(-D) \geq \varpi(s).$$

If $\lambda > 0$, the punishment can indeed increase the least offer of L and decrease the possibility of successful information leakage. However, in the single contractor case, firm 1 is not even acknowledged the status of innovation, let alone be sure about the secret deal. Therefore, $\lambda = 0$ and a disclosure punishment will not work in this case.

3. Hiring two contractors

In the leakage-free contract, extra rewards are given to the contractor, because he has higher bargaining power by secretly selling the innovation. Now, if some competition is introduced to the contractor side, then firm 1's bargaining power can be increased and it will not necessarily pay the contractor the highest possible reward. According to Holmstrom (1982), 'competition among agents with relative evaluation has merit as a device to extract information optimally.' In this section, we will demonstrate how hiring two contractors can prevent information leakage and mitigate the over-rewarding problem.

However, an immediate question with this setting is: Will two contractors increase the possibility of successful information leakage? Our answer is: if there is a disclosure punishment D, then the probability of information leakage will actually decrease! Recall from Section 2 that a disclosure punishment will not work in a single contractor case, because firm 1 is not even acknowledged the status of innovation and hence it cannot be 100% certain that the contractor has sold the innovation. With two contractors, we will demonstrate that a disclosure punishment might work because there is more chance that the defector can be identified and receive the punishment.

The Environment: Let a and b denote the two independent contractors that firm 1 hires to work

	s	n
s	$\varpi^{\mathrm{M}}, \varpi^{\mathrm{M}}$	ϖ^{H},0
n	0, ϖ^{H}	z, z

Figure 2. The relative performance scheme.

on R&D for a process innovation. As in Section 2, it is assumed that a successful innovation will reduce the production cost from c to $\hat{c}$. The two contractors[23] will be rewarded according to their relative performances (see Holmstrom, 1982). Let (r_a, r_b), with $r_k \in \{s, n\}$ for $k = a, b$, denote the respective reports by contractor a and b, and $\varpi(r_a, r_b)$ denote the relative performance rewards which are summarized as Figure 2.

The interpretation is: if both contractors report successful innovations, both are equally rewarded ϖ^M, if both report failures, both get $z > 0$; if only one contractor reports a successful innovation, he is to be paid $\varpi^H (> \varpi^M)$ and the other is paid some service fee, which is normalized to zero. All rewards will be determined in the model.

The effort space for each contractor is assumed to be the same as in Section 2, i.e., $E_k = E = \{0, \bar{e}\}$ for $k = a, b$. Also, let the same $\gamma(s|e)$ denote each contractor's probability of discovering a successful innovation and we assume that $\gamma(s|0) = 0$ and $\gamma(s|\bar{e}) > 0$. The effort cost is given by $\psi(e)$ and we assume that $\psi(0) = 0$ and $\psi(0) <; \psi(\bar{e})$.

Timing: We will consider the following timing of game: (i) Firm 1 offers a relative performance scheme to contractors a and b. Then, both contractors choose their effort independently and simultaneously; (ii) After the effort decisions and given the status of innovation, each contractor decides whether to sell the innovation and change the content of the report accordingly; and (iii) After receiving the reports, firm 1 and firm 2 play the production game defined in Section 2.

3.1. *Characterization of equilibrium*

We will solve the the game timing backward. Firstly, there can be four combinations of reports, that is, (s, s), (s, n), (n, s), and (n, n). Firm 1's production cost will be $\hat{c}$ for (s, s), (s, n), and (n, s) and the cost will be c for (n, n). Let $\sigma(r_a, r_b)$ denote the probability that firm 1 thinks that the innovation has been successful but the contractor has sold it to firm 2. The calculation is related to the status of innovation, the contractors' leakage decisions, and firm 2's outbid decision; hence, we will address the details shortly. Given this belief, the equilibrium outputs under incomplete information are given by equations (1) and (2).

3.1.1. Leakage decisions

The contractors' leakage decisions will depend on the other contractor's innovation status as well as his leakage decision. Here, we have simplified the analysis by assuming that the contractors know each other's innovation results, probably through private communications.[24] Let (θ_a, θ_b) denote the two contractors' true status of innovation. Similar to reports, there can be four combinations: (s, s), (s, n), (n, s), and (n, n). If the status is (n, n), selling the innovation is impossible for either contractor. If the status is (s, n) or (n, s), then the decision for the contractor who has s will be the same as in Section 2, and firm 2 will outbid the reward up to the highest level of $\bar{L}$. Hence, for the above two states, according to our discussion in Section 2, successful information leakage is possible and hence, firm 1 can only receive (n, n) for these three cases. Finally, if the status is (s, s), then there can be *four* decision combinations: *both contractors sell, one of two contractors sells, and none of the contractors sells.* Figure 3 depicts the resulting reports for different combinations of leakage decisions, and we now discuss each case as follows.

(i) When both of the two contractors come forward to sell the innovation, firm 2 will only buy one innovation, as one[25] innovation is sufficient to reduce the production cost to $\hat{c}$. Buying two innovations[26] will not further reduce the production cost and it will cost more. We will assume that firm 2 will select the contractor to purchase randomly. Given that firm 2 will only buy one innovation, the report combination (n, n), is not possible for the status (s, s). (ii) When only one contractor sells the innovation, firm 2 will behave as addressed in Section 2 and outbid up to $\bar{L}$. In this case, the report will be (s, n). (iii) When none of the contractors sells the innovation, the reports will be (s, s).

In sum, the following lemma concludes the connection between reports, the true states of innovation, and the contractors' leakage decisions.

	sell	not
sell	n, n	n, s
not	s, n	s, s

Figure 3. Four possible reports for $(\theta_a, \theta_b) = (s, s)$.

Lemma 4. *If the reports are (s, s), then the status must be (s, s) and none of the contractors has sold the innovation; If the reports are (s, n) or (n, s), then the status is (s, s) and one contractor has sold the innovation to firm 2; If the reports are (n, n), then the status can be (n, n), (n, s) or (s, n).*

Using Lemma 4, we can calculate firm 1's posterior belief $\sigma(r_a, r_b)$ as follows: First, notice that the reports (s, n) or (n, s) cannot come from the status (s, n) or (n, s), because the contractor with the innovation will sell it to firm 2. Moreover, the reports (n, n) can come from status (n, n), (n, s), and (s, n). Together with the leakage decisions in Lemma 4, it can be easily calculated that (i) $\sigma(s, s) = 0$; that is, if two contractors report s, then firm 1 is certain that both of them have put in effort and have not cheated; (ii) $\sigma(n, n) = \frac{2\rho\gamma(s|\bar{e})(1-\gamma(s|\bar{e}))}{\rho[2\gamma(s|\bar{e})(1-\gamma(s|\bar{e}))+(1-\gamma(s|\bar{e}))^2]+(1-\rho)}$ by applying the Bayes' rule. The interpretation is similar to $\sigma(n)$ in equation (4); (iii) $\sigma(s, n) = 1$ and $\sigma(n, s) = 1$. The reason is because if only one contractor reports s, then according to our discussion above, firm 1 is certain[27] that both of them have put in effort and the contractor reporting n has cheated.

Given firm 1's posterior belief, we can now determine the equilibrium for leakage decisions in Figure 3 for $(\theta_a, \theta_b) = (s, s)$. Recall that we have a pecuniary punishment D for a convicted theft, and the relative performance rewards are given in Figure 2. The payoffs for each decision profile are given as follows. (i) As explained above, it is not possible that both contractors[28] can sell the innovation. To express the impossibility, we can assume a negative reward for each contractor, say, $-\varepsilon$ for $\varepsilon > 0$. It can be checked that the level of ε will not affect the equilibrium; (ii) If both do not sell, then the report will be (s, s) and the rewards are ϖ^M for both contractors; (iii) If only one of them sells the innovation, then the reports will be (s, n) or (n, s) and the rewards will be $(\varpi^H, 0)$ and $(0, \varpi^H)$, respectively. Moreover, for the contractor who chooses to sell the innovation, there is an offer $L = z$ from firm 2 according to a decision rule similar to equation (5). But in this case, firm 1 can be *certain*[29] that the contractor reporting n has committed theft, which allows firm 1 to ask for damage liability[30] or punishment D from the contractor reporting n. Hence, the total benefit for the decision profiles (*sell*, *not*) and (*not*, sell) are $(z-D, \varpi^H)$ and $(\varpi^H, z-D)$, respectively. According to Section 1832 of the Economic Espionage Act 1996, this fine can be up to 10 years and fined \$500,000 or both. The point is: if D is sufficiently big, then there will exist a unique equilibrium where both contractors do not sell the innovation in the case of $(\theta_a, \theta_b) = (s, s)$.

To sum up, if the status is $(\theta_a, \theta_b) = (n, n)$, then none of the contractors can sell the innovation; if $(\theta_a, \theta_b) = (s, n)$ or (n, s), then the contractor who has s will sell; if $(\theta_a, \theta_b) = (s, s)$, then there will be an equilibrium where both agents do not sell, if D is sufficiently big.

3.1.2. *Optimal relative performance scheme*

Given the contractors leakage decisions above, we can derive the optimal rewards as follows. First of all, the IC constraints are required for effort putting. That is, let $\hat{\Pi}_k(e)$ denote contractor k's expected payoff, where

$$\hat{\Pi}_k(e) = \rho\Big\{\gamma(s|e)^2\varpi^M + \gamma(s|e)(1-\gamma(s|e))(\varpi^H)\Big\} + \Big\{\rho(1-\gamma(s|e))^2 + (1-\rho)\Big\}z - \psi(e).$$

Given the prior belief ρ, the chance for both contractors to discover successful innovations is $\gamma(e|s)^2$. In this case, both contractors will choose not to sell and hence both receive ϖ^M. The chance that only contractor k discovers the innovation is $\gamma(s|e)(1-\gamma(s|e))$, in which case, as discussed, he will sell the information and get a reward for reporting n as the other contractor. The reward will be z plus the offer L from firm 2. According to equation (5) in Section 2, L is determined by $z + L = \varpi^H$. Replacing $L = \varpi^H - z$ into the reward, the sum of rewards for this case is ϖ^H. Finally, there is an overall probability $\{\rho(1-\gamma(s|e))^2 + (1-\rho)\}$ that neither of the two contractors will discover the successful innovation, and hence the reward is z. Notice that $\hat{\Pi}_k(0) = z$.

To motivate the contractors to put in effort, it is required by the IC constraint that

$$\hat{\Pi}_k(\bar{e}) \geq z,$$

which can be simplified as:

$$\gamma(s|\bar{e})\varpi^M + (1-\gamma(s|\bar{e}))(\varpi^H) - z \geq \frac{\psi(\bar{e})}{\rho\{\gamma(s|\bar{e})}.$$

Since $\hat{\Pi}_k(0) = z$, it would be the cheapest[31] to set $z = 0$. Therefore, the cheapest reward to satisfy the IC is to set $\gamma(s|\bar{e})\varpi^M + (1-\gamma(s|\bar{e}))(\varpi^H) = \frac{\psi(\bar{e})}{\rho\{\gamma(s|\bar{e})}$. It can be calculated that the total reward that firm 1 needs to pay is

$$\rho\Big\{\gamma(s|\bar{e})^2 2\varpi^M + 2\gamma(s|\bar{e})(1-\gamma(s|\bar{e}))(\varpi^H)\Big\} + \Big\{\rho(1-\gamma(s|\bar{e}))^2 + (1-\rho)\Big\}2z.$$

Substitute $z = 0$ and this total reward becomes $2\psi(\bar{e})$.

In other words, if the effort cost $\psi(\bar{e})$ is not too high, the overall reward that firm 1 pays for hiring two contractors will be relatively lower than hiring one contractor. Moreover, unlike the single contractor case where the innovation is always leaked, there is a probability $\rho\gamma(s|e)^2$ that there is no information leakage.

In sum, in a *perfect Bayesian Nash equilibrium* of this contracting process, firm 1 determines the cheapest relative performance rewards to satisfy $\gamma(s|\bar{e})\varpi^M + (1-\gamma(s|\bar{e}))(\varpi^H) = \frac{\psi(\bar{e})}{\rho\{\gamma(s|\bar{e})}$, the contractors' leakage decisions and firm 1's posterior beliefs are described above, and given the posterior beliefs, each firm's profits are given by equations (1) and (2). The following proposition summarizes the comparison to the single contractor case.

Proposition 5. *When hiring two contractors, there exists a perfect Bayesian Nash equilibrium where the probability of successful information leakage is less and the equilibrium reward is cheaper than hiring one contractor.*

Proof. (i) Notice that in the single contractor case, there exist no leakage-free contract, and hence, the probability of successful information leakage is 1. This is higher than the probability of leakage for hiring two contractors: $1-\rho\gamma(s|\bar{e}).^2$ (ii) The total reward in this equilibrium is $2\psi(\bar{e})$, and this is smaller than hiring one contractor where the reward is higher than firm 1's total benefit from innovation. ■

Finally, it is interesting to see how information leakage will affect firm 1's revenue. Firm 1's expected revenue in this equilibrium is: $\rho\{\gamma(s|e)^2\pi_1(\hat{c},c) + 2\gamma(s|e)(1-\gamma(s|e))\pi_1(\hat{c},\hat{c})\} + \{\rho(1-\gamma(s|e))^2 + (1-\rho)\}\pi_1(c, E_{(n,n)}c_2)$. This is less than the case where two contractors are honest: $\rho\{\gamma(s|e)^2\pi_1(\hat{c},c) + 2\gamma(s|e)(1-\gamma(s|e))\pi_1(\hat{c},c)\} + \{\rho(1-\gamma(s|e))^2 + (1-\rho)\}\pi_1(c,c)$. The possibility of information leakage reduces the expected revenue because (i) firm 1 loses its cost advantage from innovation in status (s,n) and (n,s) and this is because the successful contractor will betray; (ii) firm 1 loses part of its cost advantage in status (n,n) because its suspicion that one of the contractors might have cheated reduces firm 1's expectation on firm 2's production cost.

Overall, hiring two contractors might work because under the relative performance scheme, the contractors' bargaining power has been decreased, and moreover, there is more chance that the cheating behavior can be detected, which leaves the space for the disclosure punishment to help with the leakage problem.

4. Concluding remarks

Outsourcing R&D activities has become an inevitable trend in this era of outsourcing. Due to its uncertain features, R&D outsourcing is encountered with a high risk of information leakage. This paper pointed out how the possibility of information leakage can push up the contract reward that causes the non-existence of a leakage-free contract. Also, we demonstrated how a competitive mechanism of hiring two contractors, together with a disclosure punishment, can result in a perfect Bayesian Nash equilibrium where the possibility of successful leakage is reduced and the equilibrium reward is also cheaper.

Throughout the paper, we have made several simplifications to emphasize the impacts of information leakage, and relaxing these assumptions can certainly enrich the analysis and we hope to leave that for further research. For example, we have assumed only a single R&D firm and considered only the deliberate information leakage. It would be interesting to explore the case with multiple R&D firms with one or two contractors, where the discussion from the common agency literature (see, e.g., Holmstrom and Milgrom, 1991) can help to address more issues related to information leakage.

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Notes

1. Deavers (1997) pointed out five reasons for outsourcing, including to improve company focus, to access to world-class capabilities, to accelerate benefits from reengineering, to share risks, and to have free resources for other purposes.
2. India passed the IP law in February 2005 giving greater protection for IP. This has encouraged many pharmaceutical firms to outsource their drug development activities (Balachandra, 2005).
3. Other forms of information leakage include leakage through publicly observable variables like prices (Grossman and Stiglitz, 1980; Brunnermeier, 2005); actions (Banerjee, 1992; Bikhchandani et al., 1992); collaboration (Jaffe, 1986; Perez-Castillo and Sandonis, 1996).
4. The R&D firm cannot detect the betrayal because it is not certain whether the innovation has been successful.
5. The information leakage problem can be explained as a special case of renegotiation or collusion, but we will demonstrate that the usual solution of renegotiation proof or collusion proof contract cannot solve the leakage problem. Because this kind of betrayal behaviors fit in many other fields, e.g., a client firm might bribe the auditor to misreport the financial status, this paper hopes to contribute to seeking remedies for this sort of problems.
6. We will demonstrate in Section 2 that it is without loss of generality to focus on a leakage free contract.
7. Here, firms are assumed to be symmetric in the output market. However, we will discuss the effect of an asymmetric assumption.
8. See Baiman et al. (1991), Kofman and Lawarree (1993), Kofman and Lawarree (1996) and Khalil and Lawarree (2006) for discussion on auditing theory.
9. The interested readers are referred to Lai et al. (2006).
10. The information leakage problem can be presented well in the framework with one R&D firm. With multiple R&D firms, there will be strategic correlation associated with multiple principals framework.
11. Later we will explain that firm 2's cost can possibly reduce to $\hat{c}$ if information leakage happens.
12. Otherwise, we need to discuss whether it is worthy to engage in an R&D activity for all possible ranges of $\hat{c}$.
13. This is an often-used assumption in R&D or innovation literature (see. e.g., Reinganum, 1989).
14. An alternative assumption is the Poisson distribution (see e.g., Reinganum, 1989).
15. Here, we assume that the contractor has full control over the innovation, as this is the worst case for the leakage problem. Baccara (2007) considers different extents that the contractor can control the result.

16. Notice that firm 2 cannot observe the contracting process. However, this is not critical in the case with perfect commitment.
17. Here we have simplified the setting by assuming that the contractor will not cheat on firm 2. Because the cost reduction from innovation is verifiable, firm 2 can delay the payment L until it is certain that the innovation can work.
18. Normally, lawsuits take a long time and there can be both pecuniary and non-pecuniary (i.e., in prison) punishments. Because our model considers only two stages (i.e., the first and the interim stages), we need to make this simplification for tractability.
19. Because of innovation uncertainty, firm 1 cannot observe the contractor's secret deal. However, as required by *sequential rationality* (see Kreps and Wilson, 1982), firm 1 will rationally update its beliefs for off-equilibrium path reports.
20. An interesting query with this setting is: if firm 2 has $\hat{c}$ wouldn't firm 1 infer that it has stolen the innovation? Our answer is that: since firm 1 does not know about the true status for sure, it cannot prove that the contractor has sold the innovation with another contractor.
21. We have simplified the setup by ignoring the morality or ethic concern (see e.g., Howieson, 2005) or the reputation concern from the repeated game framework (see Milgrom and Roberts, 1982).
22. Here we assume the usual breaking rule to ensue the existence of equilibrium.
23. To simplify, it is assumed that there is no other strategic interaction between the two contractors such as a collusion or a frame-up.
24. See literature on spillover in R&D, e.g., Jaffe (1986) and Perez-Castillo and Sandonis (1996).
25. We assume that the two contractors' innovations are of the same quality.
26. Buying one innovation is a dominant strategy for firm 2, given the fact that two offers have been provided. There can be another equilibrium where firm 2 buys two innovations and both contractors sell their innovations. In this case, the result is the same as in Section 2, i.e., information leakage is inevitable.
27. In fact, we will show that both (s,n) or (n,s) cannot be equilibrium. But because our beliefs are derived by the Bayes' rule, the consistency requirement by Kreps and Wilson (1982) is satisfied.
28. Keeping in mind that because report (n,n) is not possible for $(\theta_a,\theta_b)=(s,s)$, the reward is not z for each contractor.
29. As explained, this is because reports (s,n) or (n,s) cannot come from status (s,n) or (n,s).
30. Here, we assume a perfect enforcement of this punishment. See Qiu (2006) for discussion on different degrees of court enforcement.
31. Otherwise, firm 1 can increase total payoff by lowering z.

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