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The Impact of Royalty Contract Revision in a Multistage Strategic R&D Alliance

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This paper investigates the impact of royalty revision on incentives and profits in a two-stage (research and development (R&D) stage and marketing stage) alliance with a marketer and an innovator. The marketer offers royalty contracts to the innovator. We find that the potential for royalty revision leads to more severe distortions in the optimal initial royalty contracts offered by the marketer. We show that if the innovator plays a significant role in the marketing stage, the marketer should offer a low royalty rate initially and then revise the royalty rate up later. Otherwise, she should do the opposite. We identify two major effects of royalty revision. First, royalty revision provides the marketer with a flexibility to dynamically adjust royalty rates across the two stages of the alliance to better align the innovator's incentives. This *incentive-realigning effect* improves the marketer's profit. Second, royalty revision makes it harder for the marketer to obtain private information from the innovator, because the innovator worries that the marketer will take advantage of the information to revise the initial contract to a more favorable one to herself later. This *information-revealing effect* hurts the marketer's profit. We characterize in what kind of alliances marketers would benefit the most from royalty revision so that managers should clearly establish the expectation for royalty revision, and in what kind of alliances markerters would not benefit from royalty revision so that managers should commit not to revise the initial royalty contract. With royalty contracts that are contingent on the R&D outcome of the R&D stage, we find that contingent contract structure could be either *substitutable* (by fully capturing the incentive re-aligning effect) or *complementary* (by weakening the information revealing effect) to royalty revision, depending on whether the innovator plays a significant role in the marketing stage. Managers may need to use a contingent contract (if possible) either to replace or with royalty revision accordingly to improve profits.

Key words: research and development; royalty contract; renegotiation; incentives; R&D alliance

1. Introduction

In many research and development (R&D)-intensive industries it has become increasingly popular for firms to form strategic R&D alliances to innovate and commercialize new products. A recent study shows that there were more than 600 biotech-pharmaceutical alliances formed in 2007 alone, and their value increased from $30 billion to more than $90 billion between 2004 and 2007 (Global Business Insights 2008). Royalty contracts are commonly used to structure and govern biotech-pharmaceutical R&D alliances and are frequently revised (Mason et al. 2008).[1] Eli Lilly and Ligand Pharmaceuticals formed

an alliance to develop and market a drug called ONTAK for the treatment of patients with recurrent cutaneous T-cell lymphoma. ONTAK generated $25.9 million in sales in the first three quarters of 2004. In January 2005, Lilly agreed to allow Ligand to buy down a portion of the royalties payable to Lilly on sales of ONTAK with a one-time cash payment of $20 million (Ligand Pharmaceuticals 2005). Some biopharma alliances even explicitly anticipate future contract revisions in their initial agreements. In 2009, Bristol-Myers Squibb (BMS) and ZymoGenetics formed an alliance to develop PEG-Interferon lambda, a novel hepatitis C drug that could be an ideal fit with the BMS emerging portfolio of small molecule antivirals. Zymo was expected to conduct a significant portion of R&D activities in phases I and II. The initial agreement clearly stated that Zymo could opt out of the copromotion and profit sharing arrangement after the R&D stage (*Medical News Today* 2009).

Royalty contracts are often revised in R&D alliances because of several distinct features: First, an R&D

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[1] Royalty contract revisions are also widely practiced in other industries. For example, to speed the transfer of its superconductor wire technology in the market, American Superconductor Corp., a leading global supplier of superconductor products, and Pirelli Energy Cables and Systems, the world's largest power cable manufacturer, renegotiated terms in their initial strategic alliance agreement in 2002 to increase the royalty rate American Superconductor pays to Pirelli for any wire sold.

alliance normally has well-defined stages or milestones that provide natural opportunities for firms to review information and renegotiate deals. Second, firms could take the lead alternatively in different stages of the alliance. In a biopharma alliance, the biotech firm normally takes the lead in the R&D stage, and the pharmaceutical firm takes the lead in the marketing stage. Hence, the firms need to revise the initial royalty contract as their roles change across stages to dynamically align incentives in the alliance. Third, interacting with each other in the early stage(s) of the alliance, some of the firms' privately endowed information could be revealed through their actions. Learning the other firm's private information, the firm that has stronger influence on setting contract terms in the alliance could propose to revise the original contract to a more favorable one for itself.

Although royalty contract revision is widely practiced, little is known about how it impacts the incentives and performances in an R&D alliance, how different alliances should revise their royalty contracts differently, and what types of alliances would benefit the most from royalty contract revision. This paper aims to answer these questions in a stylized model of multistage R&D alliance, where an innovator (he) and a marketer (she) form an R&D alliance to jointly develop and market a new product in two sequential stages: the R&D stage and the marketing stage. The marketer and the innovator could have asymmetric information regarding the innovator's R&D capability. Before the R&D stage begins, the marketer offers a menu of royalty contracts that may or may not be contingent on the technical performance of the product that emerges from the R&D stage and asks the innovator to pick one from the menu. Each royalty contract in the menu consists of a fixed transfer and a royalty rate that will be paid to the innovator on each dollar of the revenue generated from the product. After the R&D stage, the marketer can propose to revise the initial royalty contract, and the innovator can either accept or reject the proposal. With this model, we establish the following main findings.

First, we characterize the optimal truth-telling inducing initial menu of royalty contracts and royalty revision strategy for the marketer. With royalty revision, the marketer not only needs to consider which contract an innovator would choose from the initial menu, but she also needs to consider how the innovator would react to (reject or accept) her royalty revision proposal later. To induce the innovator to choose the initial contract and react to the revision proposal truthfully, the marketer has to distort the optimal initial royalty contracts for both the more capable (high-type) and less capable (low-type) innovators. This is in sharp contrast to a well-known existing result that distortion only occurs at the low type's

contract. Furthermore, we show that if the innovator plays a significant role in the marketing stage, the marketer should offer a low royalty rate initially and then revise the royalty rate up later. Otherwise, she should do the opposite.

Second, starting with royalty contracts that are not contingent on the technical performance of the product from the R&D stage, we identify two major effects of royalty revision on the expected profit of the marketer. Royalty revision provides the marketer with the flexibility of using different royalty rates in different stages to dynamically align incentives as the alliance progresses. This *incentive-realigning effect* of royalty revision is beneficial and leads to a higher profit for the marketer. However, with royalty revision, the innovator is less willing to reveal his private information to the marketer because he knows the marketer would use this information to revise the contract later to a more favorable one for herself. This *information-revealing effect* of royalty revision makes inducing truth-telling more costly for the marketer, in turn hurting her profit. With this dissection of the effects of royalty revision we are able to predict in what types of R&D alliances marketers would benefit the most from royalty revision.

Third, with royalty contracts that are not contingent on the technical performance of the product from the R&D stage, we are able to pinpoint interesting interplays between contingent contract structure and the two major effects of royalty revision. When the innovator does not play a significant role in the marketing stage, the flexible contingent contract structure fully captures the incentive-realigning effect of royalty revision. In this case, a contingent contract is perfectly *substitutable* for royalty revision. On the contrary, when the innovator does play a significant role in the marketing stage, the contingent contract structure cannot capture the incentive-realigning effect of royalty revision, but helps weaken the information-revealing effect of royalty revision by providing more flexibility for the marketer to differentiate innovators with different types. As a result, a contingent contract enhances the value of royalty revision and is therefore *complementary* to royalty revision. Thus, depending on whether the innovator plays a significant role in the marketing stage, managers may need to use a contingent contract (if possible) either to replace or with royalty revision to improve profits.

We review related literature in §2. Section 3 presents the model. Sections 4 and 5 study noncontingent royalty contracts and contingent royalty contracts, respectively. Several extensions of the model are discussed in §6. Section 7 concludes the paper.

2. Literature Review
Our paper closely relates to the literature on innovation and licensing. Kamien and Tauman (1986) show

that the optimal licensing strategy for an innovator with a cost-reduction invention is to license its invention by a fixed-fee contract. Gallini and Wright (1990) show that a royalty can serve as a signaling device in an innovation licensing relationship with asymmetric information. Erat et al. (2007) consider a model where competitive end-product manufacturers license a technology from one upstream technology provider with symmetric information. They find that a mix of a fixed fee and royalty may be optimal if the technology provider decides to license to a large number of end-product manufacturers. Crama et al. (2008) consider the case of a risk-averse biotech innovator designing and offering a menu of three-part contracts (up-front, milestone, and royalty payments) to a risk-neutral pharmaceutical firm whose effort influences the project's final payoff. Whereas Crama et al. (2008) focus on how the innovator's risk aversion and the pharmaceutical firm's valuation determine the optimal contract structure (i.e., whether to include milestone payments or royalties) without renegotiation, we study the impact of renegotiation on royalty contracts with or without milestone payments. Savva and Scholtes (2009) study a multistage partnership between a biotech and a pharmaceutical firm. The firms have asymmetric information regarding the quality of the biotech's project. In a signaling model, they find that using royalties can cause inefficient termination of the project, and a joint venture arrangement restores the efficiency. We complement this line of literature by considering the potential for royalty contract revision and its impact in an R&D alliance with both adverse selection and moral hazard.

Our paper also relates to R&D and new product development literature (see Krishnan and Ulrich 2001, Krishnan and Loch 2005, and Loch and Kavadias 2007 for excellent reviews). In this literature, there is a small group of papers that study incentives in decentralized R&D and product development within or between firms (see Anderson et al. 2007 about offshoring R&D and Bhaskaran and Krishnan 2009 for collaborative R&D). Sommer and Loch (2009) consider incomplete incentive contracts for R&D projects with ambiguity. They construct an incomplete contract for an ambiguity neutral principal to reinstate optimal incentives for an ambiguity averse agent. Terwiesch and Loch (2004) present a model where a firm designs and produces a customized product to customers through a multistage collaborative prototyping process. They show how the firm can price the prototypes and the final product to signal its design capability to customers. Chao et al. (2009) study how funding authority and incentives affect a central manager's allocation of resources between existing product improvement and new product development, which are managed independently by two decision

makers. They find that a so-called variable funding drives higher efforts but induces the manager to focus more on existing product improvement than new product development. Mihm (2010) considers an internal cost-gaming issue in a new product development project and shows how incentive schemes, such as profit-sharing contracts and component-level target costing, can provide incentives for engineers to improve cost compliance of the project. All these papers study static incentive problems without the possibility of contract revision, which is the focus of our paper. Plambeck and Taylor (2007) study the impact of contract renegotiation in an R&D setting where a manufacturer writes capacity supply contracts with pharmaceutical companies. However, their focus is on renegotiation over capacity allocation, whereas ours is on renegotiation over royalties.

The economics literature on renegotiation is vast (see Bolton and Dewatripont 2005 for a review) and can be classified into two streams: renegotiation under adverse selection (e.g., Hart and Tirole 1988, Laffont and Tirole 1990) and renegotiation under moral hazard (e.g., Fudenberg and Tirole 1990). In the former, the agent's type is unknown to the principal; the renegotiation opportunity arises in the late period because the principal may learn the agent's private type from his contract choice, made in the early period. In the latter, the risk-averse agent exerts an effort that is unobservable to the principal; the renegotiation opportunity arises after the agent makes his effort decision but before uncertainty is resolved. Both streams of literature find that renegotiation improves ex post efficiency but may negatively impact ex ante incentives. Our paper is distinct from both streams of economics literature on renegotiation in that we study the impact of renegotiation under both adverse selection and moral hazard.

3. Model

An innovator (e.g., a biotech company) and a marketer (e.g., a pharmaceutical company) form a strategic R&D alliance to jointly explore, develop, and market a new idea conceived by the innovator. Both the innovator and the marketer are risk neutral with a reservation profit of zero. The alliance takes place in two sequential stages: the R&D stage followed by the marketing stage.

In the R&D stage, the innovator and the marketer collaborate in R&D to try to develop a product based on the idea. The innovator will exert R&D effort e_1 to conduct required R&D for the alliance, and the marketer will also contribute to the R&D by exerting R&D effort m_1. Both R&D efforts e_1 and m_1 are private actions that are not contractible. The R&D efforts are costly to both parties. The cost of exerting R&D effort

e_1 is $e_1^2/2c_i$ for the innovator, and the cost of exerting R&D effort m_1 is $m_1^2/2$ for the marketer. The coefficient c_i can be understood as a measure of the capability of the innovator in executing the R&D of the idea (see Che and Gale 2003 for a similar R&D model). To exert the same effort, it is cheaper for an innovator with a higher c_i (more capable) than for an innovator with a lower c_i (less capable). The innovator knows exactly the value of his R&D cost coefficient c_i or his capability. However, the marketer does not know the exact value of c_i. To facilitate tractability, we assume that she only knows that c_i can take one of two values c_l and c_h with $0 < c_l < c_h$, with the following probability distribution:

$$c_i = \begin{cases} c_h & \text{with probability } \rho, \\ c_l & \text{with probability } 1 - \rho. \end{cases}$$

We call an innovator with c_i an *i*-type innovator. Hence, the innovator and the marketer have asymmetric information regarding the innovator's R&D cost coefficient c_i or R&D capability. Our model with both moral hazard and information asymmetry captures the most essential natures of R&D alliances, especially biopharma alliances, as shown by empirical studies in finance and entrepreneurship (e.g., Kaplan and Stromberg 2004, Lerner 2000).

With probability $s \in (0, 1]$, the idea could turn out to be a technical success (e.g., obtaining approval by the U.S. Food and Drug Administration (FDA)) at the end of the R&D stage. The probability of technical success s captures the technical uncertainty faced by the alliance. Upon success, the technical performance of the product emerged from the R&D stage; θ is a random variable with a support on $[0, \infty)$ (i.e., once proven successful, the technical performance of the product would be nonnegative), and θ could represent how many and which indications are approved by the FDA or what restrictions (e.g., warning label) the FDA would impose on the product. The mean of θ is determined jointly by the innovator's R&D effort e_1 and the marketer's R&D effort m_1 as

$$\mathbf{E}[\theta \mid e_1, m_1] = e_1 + m_1. \tag{1}$$

An example of such a setting is a multiplicative performance function: $\theta = (e_1 + m_1)\epsilon$, where ϵ is a random variable with a support on $[0, \infty)$ with a mean 1. The realized technical performance θ is observable to both parties. With probability $1 - s$, the idea could turn out to be a technical failure (e.g., rejected by the FDA because of severe side effects) at the end of the R&D stage. In this case, the idea cannot be developed into a marketable product. Consequently, the alliance will be terminated and both parties will receive no future payoffs.

If the outcome of the R&D stage is a technical success, the alliance advances to the marketing stage, in which the product will be commercialized in the market. The total revenue from marketing the product x is driven by four factors. First, the realized technical performance of the product emerged from the R&D stage θ determines the revenue potential of the product—the higher θ is, the higher the revenue will be for the product. Second, the marketer's marketing effort m_2 will lead to a deterministic increase in the product revenue. Such marketing effort corresponds to advertising, promotions, deploying salesforces, and utilizing existing distribution channels. The cost of the marketing effort m_2 to the marketer is $m_2^2/2$. Third, the innovator would continue to exert additional R&D effort e_2 to further enhance the technical performance of the product. Such further enhancements could make the product appealing to more consumer segments in the market, in turn increasing sales. For example, after obtaining FDA approval on a new drug, a biotech firm can keep investing additional R&D effort to develop an over-the-counter version of the drug and/or to develop variations of the drug to target more indications. It also costs the innovator $e_2^2/2c_i$ to exert the additional R&D effort e_2. Finally, market demand for a new product is usually uncertain. The total revenue for the product is influenced by a random noise ε with mean 0; ε captures the market uncertainty faced by the alliance, which is independent of the technical uncertainty in the R&D stage.[2]

Given the realized technical performance of the product θ, the innovator's technical supporting effort e_2, and the marketer's marketing effort m_2, the total revenue collected from selling the product is determined by the following additive form:

$$x = \theta + v e_2 + \lambda m_2 + \varepsilon, \tag{2}$$

where $v \geq 0$ and $\lambda \geq 0$. The coefficients v and λ measure, respectively, the effectiveness of the innovator's additional R&D effort and the marketer's marketing effort in enhancing the revenue of the product. For a product with a high value of v, the innovator has a great potential to extend the success of the product in the market with additional follow-up R&D effort. Hence, the innovator would play a significant role in improving the sales of the product in the marketing stage of the alliance. For such a product, after the

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[2] The model can easily incorporate potential reduction in market uncertainty between the R&D stage and the marketing stage (see Bhattacharya et al. 1998). For example, we can consider that in addition to θ, the two parties also observe a signal about the market uncertainty ε. Such a signal contains information about ε, thereby reducing the market uncertainty. All of our qualitative results hold with such an extension.

Figure 1   Sequence of Events in the Alliance
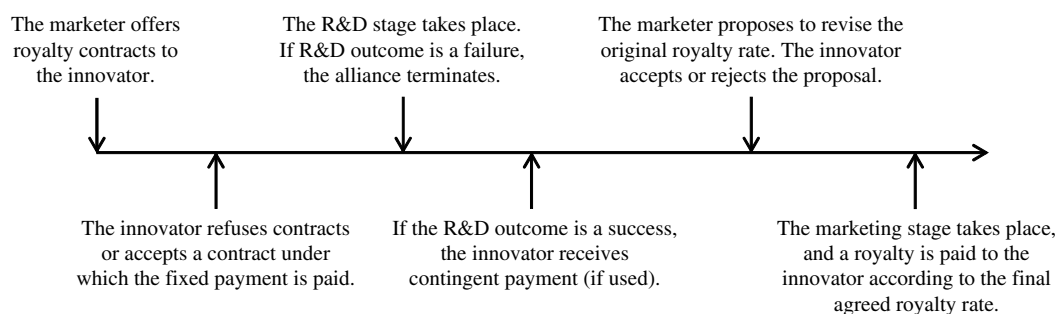
basic R&D in the first stage, there could be plenty of opportunities to develop variations of the product (e.g., a children's version or an over-the-counter version) to target broader market segments after the initial discovery. In contrast, for a product with a low value of v, after the initial R&D there is not much room for follow-up R&D by the innovator to enhance the technical performance of the product and thereby increase revenue. It is mainly up to the marketer to promote the product to generate higher sales. An example of such a product could be a drug that targets a single indication or condition (e.g., PEG-Interferon lambda for hepatitis C). After the initial discovery of the drug, the potential for additional follow-up R&D to extend the drug to other indications or market segments is limited. In such a case, the success of the drug in the market now critically hinges on the marketing ability of the marketer. When λ is large, it implies that the marketer is very capable and effective in marketing the product. Such a product could be a blockbuster drug, which large pharmaceutical firms' sales organizations are normally designed to market. When λ is small, that indicates that the marketer is less efficient or the marketing effort has insignificant impact on the drug sales (e.g., a niche drug that targets a rare indication with small market size such as Ligand's ONTAK).

The marketer takes the lead to design and offer contracts to the innovator. The sequence of events is illustrated in Figure 1. We consider royalty contracts that are not contingent on the technical performance θ as well as royalty contracts that are contingent on θ. Because of her imperfect information on c_i, the marketer offers a menu of royalty contracts and asks the innovator to pick one contract to report his type. We focus on separating contracts that induce truth-telling from the innovator. However, we want to point out that separating contracts may not perform better than semiseparating and pooling contracts. Analyzing semiseparating and pooling contracts and comparing them with separating contracts would be interesting future research. The fixed payment will be made according to the contract chosen by the innovator.

Then the innovator exerts R&D effort e_1, and the marketer also exerts her R&D effort m_1. If the R&D outcome is a failure, the alliance is terminated. Otherwise, the technical performance θ is realized and payment is made if the contract is contingent on θ. After observing θ, the marketer could update her belief about the innovator's type and propose to revise the royalty contract chosen by the innovator. The innovator can either reject the marketer's royalty contract-revising proposal and stick to the initial royalty contract or accept the marketer's proposed revision to switch to a new royalty contract. The innovator's right to reject the marketer's contract-revision proposal prevents hold-up from happening in our model. The marketing stage starts and the innovator exerts additional R&D effort e_2, and the marketer exerts marketing effort m_2. The total revenue of the product x is realized and the royalty is paid to the innovator according to the final royalty contract.

4. Royalty Contracts Not Contingent on θ

We start with royalty contracts that are not contingent on the technical performance θ at the end of the R&D stage. We will call this type of royalty contract a "noncontingent royalty contract." The marketer offers a menu of royalty contracts $\{\alpha_i, t_i\}$, $i \in \{l, h\}$ to the innovator and asks him to choose one. Under a royalty contract, the fixed transfer t_i will be made before R&D takes place and the innovator is promised a royalty payment of $\alpha_i x$ at the end of the marketing stage. Thus, the payments under this type of royalty contract are not contingent on θ directly. The marketer may use a noncontingent royalty contract for reasons such as it being too costly or tedious to verify and contract on θ, or θ being simply not verifiable and contractible in some cases. We focus on separating contracts that induce truth-telling from the innovator, and our objective is to characterize the optimal menu of royalty contracts that maximizes the marketer's expected profit.

The marketer and innovator are engaged in a multistage game with incomplete information. Thus,

our solution concept is perfect Bayesian equilibrium (see Fudenberg and Tirole 1991, pp. 331–333, for the definition and requirements for this equilibrium concept). Let $\mu_1(i)$ be the marketer's belief of the innovator's type in the R&D stage after observing that the innovator has chosen the contract (α_i, t_i). Because we focus on separating contracts that induce truth-telling, $\mu_1(i) = i$ for $i = \{h, l\}$; i.e., the marketer's belief should be consistent with the innovator's equilibrium contract choice. Given that contract (α_i, t_i) was chosen before the R&D stage, let $\mu_2(i, \theta)$ be the marketer's belief of the innovator's type after observing the realized technical performance θ. The perfect Bayesian equilibrium requires that beliefs must satisfy Bayes' rule, suggesting that $\mu_2(i, \theta) = i$ for $i = \{h, l\}$ and any $\theta \geq 0$. It is unnecessary to specify the marketer's belief of the innovator's type after observing the innovator's response to (i.e., accepting or rejecting) the contract revision because that belief has no impact on the subsequent effort decisions. This belief structure satisfies the consistency check on any off-equilibrium path because the information set (i, θ) is always on the equilibrium path for $i = \{h, l\}$ and $\theta \geq 0$; that is, any $\theta \geq 0$ is possible under the equilibrium effort decisions for both types in the R&D stage.

4.1. Revision of the Initial Royalty Contract

Suppose that the innovator chose the contract (α_i, t_i) from the initial contract menu and the realized technical performance is θ conditional on a technical success at the end of the R&D stage. Observing the innovator's contract choice i and the realized θ, the marketer forms the belief of the innovator's type $\mu_2(i, \theta) = i$ and then proposes to revise the royalty rate to β_i with a fixed transfer γ_i. The innovator can either accept or reject the proposal.

Consider the case where the innovator rejects the marketer's contract revision proposal and sticks to his initial contract choice (α_i, t_i). Then the innovator will decide his additional R&D effort e_2 to maximize his expected profit, while the marketer simultaneously decides her marketing effort m_2 to maximize her own expected profit. With efforts e_2 and m_2, the innovator's expected profit at the end of the marketing stage (excluding the fixed transfer t_i and the sunk cost of his R&D effort e_1 in the R&D stage) is $\alpha_i(\theta + \nu e_2 + \lambda m_2) - e_2^2/2c_i$ which is maximized at $e_2 = \alpha_i \nu c_i$. The marketer's expected profit (excluding the fixed transfer t_i and the sunk cost of her R&D effort m_1 in the R&D stage) is $(1 - \alpha_i)(\theta + \nu e_2 + \lambda m_2) - m_2^2/2$, which is maximized at $m_2 = (1 - \alpha_i)\lambda$. Hence, substituting e_2 and m_2, by rejecting the revision proposal, the innovator's expected profit in the marketing stage would be (let π denote the innovator's expected profit, and the subscript r represent that the innovator *rejects* the revised contract):

$$\pi_r(\alpha_i, \theta) = \alpha_i[\theta + \alpha_i \nu^2 c_i/2 + (1 - \alpha_i)\lambda^2]. \quad (3)$$

Now we consider the case when the innovator accepts the marketer's revised royalty rate β_i. Then the innovator's expected profit at the end of the marketing stage would be $\beta_i(\theta + \nu e_2 + \lambda m_2) - e_2^2/2c_i + \gamma_i$, which is maximized at $e_2 = \beta_i \nu c_i$. The marketer's expected profit is $(1 - \beta_i)(\theta + \nu e_2 + \lambda m_2) - m_2^2/2 - \gamma_i$, which is maximized at $m_2 = (1 - \beta_i)\lambda$. Hence, when the innovator accepts the revised royalty rate, his expected profit would be (let the subscript a represent that the innovator accepts the revised contract)

$$\pi_a(\beta_i, \gamma_i, \theta) = \beta_i[\theta + \beta_i \nu^2 c_i/2 + (1 - \beta_i)\lambda^2] + \gamma_i, \quad (4)$$

and the marketer's expected profit (denoted by Π) in the second stage, based on her belief, is

$$\Pi_2(\beta_i, \gamma_i \mid \theta)$$
$$= (1 - \beta_i)[\theta + \beta_i \nu^2 c_i + (1 - \beta_i)\lambda^2/2] - \gamma_i. \quad (5)$$

Therefore, if the marketer wants the innovator to accept the proposed new contract, she has to make sure that the innovator would do no worse under the new contract than under the initial contract. In other words, the proposed new contract must be Pareto improving. The marketer's contract revision problem for the type i innovator can be written as[3]

$$\max_{0 \leq \beta_i \leq 1, \, \gamma_i} \Pi_2(\beta_i, \gamma_i \mid \theta)$$
$$\text{s.t. } \pi_r(\alpha_i, \theta) \leq \pi_a(\beta_i, \gamma_i, \theta). \quad (6)$$

The following proposition characterizes the optimal contract revision strategy for the marketer.

PROPOSITION 1. *Assume the innovator chose the contract (α_i, t_i) from the initial contract menu and the realized technical performance of the product conditional on a technical success is θ at the end of the R&D stage. It is optimal for the marketer to revise the royalty rate α_i in the initial contract to*

$$\beta_i^* = \frac{\nu^2 c_i}{\nu^2 c_i + \lambda^2}, \quad (7)$$

in exchange for a fixed transfer:

$$\gamma_i^*(\theta) = \alpha_i\left(\theta + \frac{\alpha_i \nu^2 c_i}{2} + (1 - \alpha_i)\lambda^2\right)$$
$$- \beta_i^*\left(\theta + \frac{\beta_i^* \nu^2 c_i}{2} + (1 - \beta_i^*)\lambda^2\right). \quad (8)$$

It is worth noting that β_i^* in (7) is increasing in c_i, which implies $\beta_h^* \geq \beta_l^*$; i.e., the high type will get a higher royalty rate than the low type. The optimal

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[3] Under this contract revision problem, it is guaranteed that the marketer would do no worse than not revising the initial royalty α_i, because sticking to the initial royalty α_i (i.e., letting $\{\beta_i, \gamma_i\} = \{\alpha_i, 0\}$) is a feasible solution to the contract revision problem.

revised royalty rate β_i^* is forward-looking and does not depend on the realized technical performance of the product θ. It reflects the main reason for the marketer to revise the initial contract: After the innovator's R&D effort e_1 is sunk and θ is realized after the R&D stage, there is a need to realign the innovator's incentive in the marketing stage by revising the initial royalty rate. Specifically, β_i^* is increasing in the coefficient v but decreasing in the coefficient λ. As discussed above, with a high value of v, the innovator will play a significant role in the marketing stage by exerting additional R&D effort e_2. Therefore, it is important to motivate the innovator to exert higher effort e_2 with a higher royalty rate. In contrast, in an extreme case where $v = 0$ (i.e., the innovator would not contribute at all in the marketing stage), we have $\beta_i^* = 0$: there is no need to motivate him to work hard anymore, so the royalty rate should be revised to 0. Essentially, the marketer would offer a fixed payment $\gamma_i^*(\theta)$ to ask the innovator to opt out of the alliance. As discussed before, such a product could be a drug targeting a single condition with large market size. For such a product (e.g., PEG-Interferon lambda for hepatitis C, with which an estimated 170 million people worldwide are infected), the big pharma (e.g., BMS) normally would allow the small biotech (e.g., Zymo-Genetics) to opt out. On the contrary, when λ is high the marketer contributes to the marketing stage more and would rely less on the innovator's contribution. So the marketer would reduce the innovator's royalty rate. Another interesting extreme case is $\lambda = 0$—i.e., the marketer cannot contribute to the marketing stage at all—where we have $\beta_i^* = 1$: the marketer should opt out of the alliance in exchange for a fixed payment. Such a product could be a niche drug targeting a rare condition (e.g., Ligand's ONTAK for cutaneous lymphoma) for which the big pharma's (e.g., Lilly's) marketing effort has insignificant impact on its sales.

Unlike the royalty rate β_i^*, the fixed transfer $\gamma_i^*(\theta)$ in the revised contract depends on both the initial contract (α_i, t_i) chosen by the innovator and the realized technical performance θ, as well as the coefficients v and λ. The main purpose of the fixed payment $\gamma_i^*(\theta)$ is to make sure that the innovator would accept the revised contract. The initial contract (α_i, t_i) and θ determine the innovator's status quo before the marketing stage, and thus his willingness to accept the revised contract. Although both parties anticipate the initial royalty rate α_i will be revised in the future, the initial contract still can motivate the innovator to exert higher R&D effort e_1 to gain a preferable status quo before facing royalty revision.

4.2. Initial Menu of Royalty Contracts
The marketer offers a menu of royalty contracts $\{\alpha_i, t_i\}$, where $i = \{l, h\}$, under which a type i innovator would

voluntarily pick the contract (α_i, t_i) from the menu to truthfully reveal his type, i. When the innovator does this, he will anticipate that the marketer will propose a Pareto-improving contract, specified in Proposition 1, after the R&D stage. To figure out how the marketer can induce truth-telling from the innovator, let us consider the innovator's incentive to deviate from the contract that is designed for his type.

Assume the type i innovator purposely chooses the contract (α_j, t_j), where $j \neq i$, to hide his type i from the marketer. By doing this, he knows that after the R&D stage, if the outcome is a success, he would receive a proposal from the marketer to revise the royalty rate α_j to β_j^* in exchange for a fixed transfer $\gamma_j^*(\theta)$.[4] He will have two options at that time: reject the contract revision proposal or accept it. If he rejects the proposal and sticks to the initial contract (α_j, t_j) he picked, the type i innovator's expected profit when he chooses the contract (α_j, t_j) at the beginning of the R&D stage would be

$$\pi_r(i, j) = \max_{e_1 \geq 0, e_2 \geq 0} s\left[\alpha_j(e_1 + m_1 + ve_2 + \lambda m_2) - \frac{e_2^2}{2c_i}\right] - \frac{e_1^2}{2c_i} + t_j,$$

which implies that $e_1^* = \alpha_j s c_i$ and $e_2^* = \alpha_j v c_i$. In this case the marketer would exert R&D effort $m_1^* = (1 - \alpha_j)s$ and marketing effort $m_2^* = (1 - \alpha_j)\lambda$ (note that after the innovator rejects the revision, the marketer may update her belief about the innovator's type; however, it will not impact the marketer's marketing effort decision).

Now consider the case that the innovator accepts the contract revision proposal after the R&D stage. Given the technical performance θ after a technical success, the innovator's expected profit in the second stage (excluding the sunk effort cost associated with e and the fixed transfer t) is $\beta_j^*(\theta + ve_2 + \lambda m_2) + \gamma_j^*(\theta) - e_2^2/2c_i$, which implies that $e_2^* = \beta_j^* v c_i$. Note that the marketer would exert marketing effort $m_2^* = (1 - \beta_j^*)\lambda$. Substituting e_2^* and m_2^*, the innovator's expected profit at the beginning of the R&D stage is

$$\pi_a(i, j) = \max_{e_1 \geq 0} s\left[\alpha_j\left(e_1 + m_1 + \frac{v^2 \alpha_j c_j}{2} + (1 - \alpha_j)\lambda^2\right) + \frac{v^2 \beta_j^{*2}(c_i - c_j)}{2}\right] - \frac{e_1^2}{2c_i} + t_j,$$

which implies that $e_1^* = \alpha_j s c_i$.

Let $\pi(i, i) \equiv \pi_a(i, i)$ for $i = \{l, h\}$, which is the type i innovator's expected profit when he truthfully reveals

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[4] When the type i pretends to be a type j innovator by choosing the contract (α_j, t_j), the marketer's revision strategy is based on her belief about the innovator's type, which is $\mu_2(j, \theta) = j$.

his type by choosing contract (α_i, t_i) and then accepts the marketer's Pareto improving proposal to revise the initial contract to $(\beta_i^*, \gamma_i^*(\theta))$, as specified in Proposition 1. In this case, plugging in the corresponding optimal efforts e_1^*, e_2^*, and m_2^*, and recalling that $\gamma_i^*(\theta)$ is a linear function of θ, the marketer's expected profit when the type i innovator truthfully reveals his type is given as

$$\Pi(i, i) = \max_{m_1 \geq 0} \left\{ s(1-\beta_i^*) \left(\alpha_i s c_i + m_1 + v^2 c_i \beta_i^* + \frac{1-\beta_i^*}{2} \lambda^2 \right) - s\gamma_i^*(\alpha_i s c_i + m_1) - \frac{m_1^2}{2} - t_i \right\}.$$

Therefore, the marketer's initial contract design problem, denoted by (**P1**), can be written as

$$(\textbf{P1}) \quad \max_{\alpha_h, \alpha_l, t_h, t_l} \{\rho\Pi(h, h) + (1-\rho)\Pi(l, l)\}$$

$$\text{s.t.} \quad \pi(h, h) \geq \pi_r(h, l), \qquad \text{(IC}h\text{–r)}$$

$$\pi(h, h) \geq \pi_a(h, l), \qquad \text{(IC}h\text{–a)}$$

$$\pi(l, l) \geq \pi_r(l, h), \qquad \text{(IC}l\text{–r)}$$

$$\pi(l, l) \geq \pi_a(l, h), \qquad \text{(IC}l\text{–a)}$$

$$\pi(h, h) \geq 0, \qquad \text{(IR}h\text{)}$$

$$\pi(l, l) \geq 0. \qquad \text{(IR}l\text{)}$$

Unlike the traditional adverse selection problem in which each type has only one incentive compatibility constraint, there are two incentive compatibility constraints for each type of innovator in our problem. In our model, not only is the marketer concerned that one type of innovator could mimic the other, but she is also concerned about how that innovator would react to (i.e., accept or reject) the future contract revision proposal. For the high type, constraint ICh–r (ICh–a) ensures that truth-telling is better than mimicking the low type and then *rejecting* (*accepting*) the contract revision proposal intended for the low type in the future. These two IC constraints, together with the individual rationality constraint (IRh), guarantee that the high type will voluntarily choose contract (α_h, t_h) to truthfully reveal his type. Similarly, for the low type, the two corresponding IC constraints (ICl–r) and (ICl–a) together with the IR constraint (IRl) ensure truth-telling. A key observation in solving the traditional adverse selection problem is that the low type's incentive compatibility constraint will not bind in the optimal solution and thus can be ignored to simplify the problem (see Bolton and Dewatripont 2005, Chap. 2). In other words, it is not necessary for the contract designer to worry about the possibility that the low type mimics the high type. Unfortunately, this observation does *not* hold in our model. In problem (**P1**), both incentive compatibility constraints for

the low type (ICl–r) and (ICl–a) could bind at the optimal solution.

We first define several useful notations: $\alpha_1 = c_h/(1+c_h)$, $\alpha_2 = c_l/[1 + c_l + (\rho/(1-\rho))(c_h - c_l)]$, $\alpha_3 = c_l/[1 + c_l + \rho/(s(1-\rho))(s + v^2)(c_h - c_l)]$, $\varpi_1 = [(\alpha_1^2(s + v^2) - s\alpha_2^2)/v^2]^{1/2}$, and $\varpi_2 = [(s + v^2)\alpha_3^2 - s\alpha_1^2]/v^2$. The following proposition characterizes the optimal initial menu of royalty contracts which the marketer should offer to the innovator before the R&D stage starts.

PROPOSITION 2. *Given the marketer's Pareto-improving contract revision strategy* $\{\beta_i^*, \gamma_i^*(\theta)\}$ *for* $i \in \{l, h\}$, *specified in Proposition 1, (i) the optimal initial menu of royalty contracts that are not contingent on* θ, $\{\alpha_i^*, t_i^*\}$ *for* $i \in \{l, h\}$ *offered by the marketer is characterized as*

Case	Conditions	Binding constraints	Optimal initial royalty rates, α_h^*, α_l^*
1	$\beta_h^{*2} \leq \varpi_2$	ICh–r, ICl–a	$\alpha_l^* \leq \alpha_3$, $\alpha_h^* \geq \alpha_1$
2	$\beta_l^* \leq \alpha_3$, $\beta_h^{*2} > \varpi_2$	ICh–r	$\alpha_l^* = \alpha_3$, $\alpha_h^* = \alpha_1$
3	$\alpha_3 < \beta_l^* \leq \alpha_2$	ICh–r, ICh–a	$\alpha_l^* = \beta_l^*$, $\alpha_h^* = \alpha_1$
4	$\alpha_2 < \beta_l^* \leq \varpi_1$	ICh–a	$\alpha_l^* = \alpha_2$, $\alpha_h^* = \alpha_1$
5	$\varpi_1 < \beta_l^*$	ICh–a, ICl–r	$\alpha_l^* \leq \alpha_2$, $\alpha_h^* \geq \alpha_1$

and the optimal initial fixed payment t_i^* *is set accordingly to ensure the constraints specified in the second column in the above table and the constraint* (IRl) *binding; and (ii) if the innovator and the marketer have symmetric information (i.e., $c_h = c_l = c$), the optimal initial royalty contract* $\{\alpha^*, t^*\}$ *offered by the marketer is*

$$\alpha^* = \frac{c}{1+c},$$

and the optimal initial fixed payment t^* *is set to ensure the innovator's IR constraint binding.*

Because the innovator anticipates the contract revision after the R&D stage, the optimal revised royalty rates β_l^* and β_h^* are critical in determining the innovator's incentives and thereby the optimal initial menu of royalty contracts.[5] Five mutually exclusive and exhaustive cases can arise. In Case 1, β_h^* is very small ($\beta_h^{*2} \leq \varpi_2$), which implies that β_l^* is even smaller (recall that $\beta_h^* \geq \beta_l^*$). If the high type mimics the low type by choosing contract $\{\alpha_l^*, t_l^*\}$ in the initial menu, he would reject the contract revision proposal with the even smaller royalty rate β_l^* in the future. As a result, constraint ICh–r is binding while constraint ICh–a is not. Interestingly, if the low type mimics the

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[5] Because β_i^* is monotone in v and λ (see Proposition 1), the discussions on how β_l^* and β_h^* influence the initial contract menu can be easily mapped to how v and λ would influence the initial contract menu.

high type by choosing contract $\{\alpha_h^*, t_h^*\}$ in the initial menu, he would actually accept the contract-revision proposal with the very small royalty rate $\beta_h^{*2} \leq \varpi_2$ in the future. Thus, although constraint ICl–r is not binding, constraint ICl–a is, which is in sharp contrast to the traditional adverse selection problem, in which the low type's IC constraint would never bind. With one more binding constraint ICl–a, the optimal initial royalty rate for the high type (low type) is distorted higher (lower) from the corresponding solution for the high type (low type) in the traditional adverse selection problem (i.e., $\alpha_h^* \geq \alpha_1$ and $\alpha_l^* \leq \alpha_3$) in order to enlarge the gap between α_l^* and α_h^* to induce truth-telling.

In Case 2, β_h^* becomes higher (satisfying $\beta_h^{*2} > \varpi_2$), but β_l^* is still small ($\beta_l^* \leq a_3$). Constraint ICh–r is still binding because the high type will reject the still small β_l^* in the contract revision. However, constraint ICl–a becomes nonbinding because the low type now is not willing to accept the higher β_h^* in the contract revision. So the problem in Case 2 is similar to the traditional adverse selection problem in which only the high type's IC constraint is binding. Therefore, the optimal initial contract menu in Case 2 resembles the solution in a traditional adverse selection problem ($\alpha_h^* = \alpha_1$ and $\alpha_l^* = \alpha_3$).

When the revised royalty rates β_l^* and β_h^* keep going higher, we have Cases 3–5. The intuition for Cases 4 and 5 parallels the one for Cases 1 and 2. The only difference is that in Cases 4 and 5 both β_l^* and β_h^* are high, so that if the high type mimics the low type, he would keep pretending to be a low type by accepting the revised royalty rate β_l^*. Therefore, in Cases 4 and 5, constraint ICh–a is always binding, whereas constraint ICh–r is not. Case 3 is an interesting case in which the low type's royalty rate will not be revised (i.e., $\beta_l^* = \alpha_l^*$) in the model. In this case, both ICh–a and ICh–r are binding. Because the low type's IC constraints are not binding, as in Cases 2 and 4, the solution of Case 3 is similar to the one of a traditional adverse selection problem ($\alpha_h^* = \alpha_1$ and $\alpha_l^* = \beta_l^* \leq \alpha_2$).

Part (ii) of Proposition 2 derives a special case, where the innovator and the marketer have symmetric information regarding the innovator's capability.[6] With symmetric information, it is not necessary to offer a menu of contracts, and a single contract would be enough. Hence, the five cases in part (i) would simply reduce to a single case, because the mimicking incentives would not exist. This special case will be

useful for us to pinpoint the impact of royalty revision in a later part of the paper.

In practice, an important decision for managers is whether to offer a low royalty rate initially and then to renegotiate to revise the royalty rate up later or to do the opposite by offering a high royalty rate initially and then renegotiate to revise the royalty rate down later. The following proposition characterizes conditions under which the marketer should offer to revise the initial royalty rate up or down for low- and high-type innovators.

PROPOSITION 3. (i) *If*

$$\lambda \leq \upsilon \sqrt{1 + (\rho(c_h - c_l)/(1 - \rho))(1 + \upsilon^2/s)},$$

the marketer should offer the low-type innovator a revising-up contract (i.e., $\beta_l^* \geq \alpha_l^*$). Otherwise, the marketer should offer the low-type innovator a revising-down contract (i.e., $\beta_l^* < \alpha_l^*$). (ii) *If $\lambda \leq \upsilon$, the marketer should offer the high-type innovator a revising-up contract (i.e., $\beta_h^* \geq \alpha_h^*$). Otherwise, the marketer should offer the high-type innovator a revising-down contract (i.e., $\beta_h^* < \alpha_h^*$).*

We only discuss intuitions for the revising-up case that intuitions for revising-down case mirror. Note that the condition in part (i) is less restrictive than the one in part (ii), which implies that the low type is more likely to receive a revising-up contract than the high type. As we discussed, the potential for royalty revision leads to more severe distortion in the initial contracts: the high type receives a higher royalty rate, whereas the low type receives a lower royalty rate than the corresponding ones under the traditional adverse selection model without royalty revision. Thus, after the adverse selection problem is resolved after the R&D stage, the marketer is more likely to revise the overly distorted royalty rates for the high type down and for the low type up correspondingly to restore the efficiency in the marketing stage.

The condition for revising-up for the high type in part (ii) only depends on υ and λ, whereas in addition to υ and λ, the condition for revising-up for the low type in part (i) also depends on s, ρ, and $c_h - c_l$, which determine how low the second best royalty rates would be distorted. It is interesting that, all else being equal, the condition in part (i) is more likely to hold when the technical success probability s is small. The innovator's R&D effort would create less expected value for the alliance when s is small. So when negotiating the low type's royalty rate down, the marketer would be less concerned about hurting the innovator's incentive in exerting R&D effort. This leads to a low initial royalty rate for the low type that will likely be revised up later.

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[6] The special case can be derived from part (i) by using $c_h = c_l = c$. There are other equivalent ways of obtaining this special case, such as setting $\rho = 0$ or $\rho = 1$. The analysis and results will be identical.

The revising-up conditions for both types in Proposition 3 are more likely to hold when v is high and λ is low. Because the innovator exerts efforts in both stages, with a high v or/and a low λ (as discussed in the model section, this could represent a niche drug such as Ligand's ONTAK), the innovator potentially can contribute a great deal in generating revenue for the product in the marketing stage, whereas the marketer cannot. As a result, it is critical to motivate the innovator to do so in the marketing stage. Therefore, the marketer should anticipate revising the initial royalty rate up after the R&D stage is completed (as Eli Lilly did with Ligand) to boost the incentive for the innovator to exert higher R&D effort e_2 in the marketing stage. Everything else being equal, the conditions for revising up would always hold for a high enough v or/and a low enough λ. On the contrary, when v is low or λ is high (this could represent a drug that targets a single condition with large market size such as Zymo's PEG-Interferon lambda), the opposite argument would be true, and the marketer should revise the initial royalty rate down for the innovator (as BMS did with Zymo). In fact, in the extreme case of $v = 0$, the marketer would ask the innovator to opt out of the alliance in the marketing stage by reducing the royalty rate to zero.

4.3. Impact of Royalty Contract Revision

We now examine the impact of royalty contract revision in detail. We use a benchmark case in which the marketer offers the innovator a menu of royalty contracts $\{\hat{\alpha}_i, \hat{t}_i\}$, where $i = \{l, h\}$, and will *not* revise the royalty rates in the future.

4.3.1. A Benchmark: Royalty Contracts Without Revision. In this benchmark case, the marketer still designs the contract menu $\{\hat{\alpha}_i, \hat{t}_i\}$ such that a type i innovator would voluntarily pick the contract $(\hat{\alpha}_i, \hat{t}_i)$ from the menu to truthfully reveal his type i. Assume the type i innovator tries to hide his type from the marketer by purposely choosing the contract $(\hat{\alpha}_j, \hat{t}_j)$, where $j \neq i$. Because the contract chosen will not be revised in the future, the type i innovator's expected profit when he chooses the contract $(\hat{\alpha}_j, \hat{t}_j)$ at the beginning of the R&D stage would be

$$\hat{\pi}(i, j)$$

$$= \max_{e_1 \geq 0, e_2 \geq 0} \left\{ s \left[\hat{\alpha}_j (e_1 + m_1 + v e_2 + \lambda m_2) - \frac{e_2^2}{2c_i} \right] - \frac{e_1^2}{2c_i} + \hat{t}_j \right\}.$$

Let $\hat{\pi}(i, i)$ for $i = \{l, h\}$ be the type i innovator's expected profit when he truthfully reveals his type by choosing contract $(\hat{\alpha}_i, \hat{t}_i)$, and $\hat{\Pi}(i, i)$ be the marketer's expected profit when the type i innovator truthfully reveals his type. The marketer's contract

design problem without revision, denoted by (**P2**), can be written as

$$\textbf{(P2)} \quad \max_{\hat{\alpha}_h, \hat{\alpha}_l, \hat{t}_h, \hat{t}_l} \{\rho \hat{\Pi}(h, h) + (1 - \rho)\hat{\Pi}(l, l)\}$$

$$\text{s.t.} \quad \hat{\pi}(h, h) \geq \hat{\pi}(h, l), \qquad (\text{IC}h)$$

$$\hat{\pi}(l, l) \geq \hat{\pi}(l, h), \qquad (\text{IC}l)$$

$$\hat{\pi}(h, h) \geq 0, \qquad (\text{IR}h)$$

$$\hat{\pi}(l, l) \geq 0. \qquad (\text{IR}l)$$

Without any royalty revision, the marketer faces a traditional adverse selection problem in which each type only has one incentive compatibility constraint (i.e., ICh and ICl, respectively). Using a standard solution technique, the optimal menu of royalty contracts $\{(\hat{\alpha}_h^*, \hat{t}_h^*), (\hat{\alpha}_l^*, \hat{t}_l^*)\}$, as well as the optimal royalty contract $(\hat{\alpha}^*, \hat{t}^*)$ under symmetric information, are characterized in the appendix. Let $\hat{\Pi}^*$ denote the marketer's optimal expected profit under program (**P2**).

4.3.2. Incentive-Realigning Effect. We start with the special case in which the innovator and the marketer have symmetric information (i.e., $c_h = c_l = c$). This special case allows us to identify one key effect of royalty revision in a crystal clear way.

PROPOSITION 4. *With symmetric information ($c_h = c_l = c$) under royalty contracts that are not contingent on θ, (i) the marketer's optimal expected profit with royalty revision, Π^*, is no less than her optimal expected profit without royalty revision, $\hat{\Pi}^*$ (i.e., $\Pi^* - \hat{\Pi}^* \geq 0$). All else being equal, there exists a threshold $\bar{v} \in [0, \infty)$ such that (ii) for $v < \bar{v}$, the marketer will offer revise down contracts with the innovator (i.e., $\alpha^* > \beta^*$), and the benefit of royalty revision $\Pi^* - \hat{\Pi}^*$ is strictly positive and decreasing in v; (iii) for $v > \bar{v}$, the marketer will offer revise up contracts with the innovator (i.e., $\alpha^* < \beta^*$), and the benefit of royalty revision $\Pi^* - \hat{\Pi}^*$ is strictly positive and increasing in v; and (iv) for $v = \bar{v}$, the marketer will not revise the contract (i.e., $\alpha^* = \beta^* = \hat{\alpha}^*$ and $\gamma^*(\theta) = 0$), and the benefit of contract revision $\Pi^* - \hat{\Pi}^* = 0$.*

Part (i) of Proposition 4 indicates that without asymmetric information, the marketer will do no worse with royalty revision than without it. Mathematically speaking, the marketer has four contract parameters $(\alpha^*, t^*, \beta^*, \gamma^*)$ with royalty revision rather than only two $(\hat{\alpha}^*, \hat{t}^*)$ without royalty revision, which gives her more flexibility with royalty revision. With more flexibility, it is not surprising that the marketer would do no worse with royalty revision. Proposition 4 also reveals one important benefit of royalty revision to the marketer, which we call the *incentive-realigning effect*. As parts (ii) and (iii) of the proposition jointly indicate, the benefit of contract revision is stronger when the effectiveness coefficient of the

innovator's R&D effort in the marketing stage v takes extreme values (either very high or very low). The value of the effectiveness coefficient of the innovator's R&D effort in each of the two stages (1 in the R&D stage and v in the marketing stage) reflects the degree of importance of motivating the innovator to exert R&D effort in the stage. When v takes extreme values, it will be very different from its counterpart coefficient in the R&D stage (i.e., fixed at 1), which implies that very different royalty rates are needed at the two stages, respectively, to give the innovator any incentive to exert effort. In other words, there is an imbalance between the two stages in terms of incentive provision for the innovator. Royalty revision provides a means for the marketer to respond to such an imbalance by offering two different royalty rates in the two stages to realign the incentives in the alliance.

When v is very high (very low), the marketer has a far stronger (weaker) need to motivate the innovator to exert higher R&D effort in the marketing stage than in the R&D stage. As a result, the marketer would offer the innovator a higher (lower) royalty rate (β^*) before the marketing stage starts by revising the initial royalty rate α^* up (down) to β^*. In May 2008, Alseres Pharmaceuticals and BioAxone Therapeutic revised their agreement for Cethrin, a drug Alseres developed to promote nerve repair. Alseres believed that Cethrin also had good potential in other indications, such as bone repair, oncology, and eye disease. This is similar to a high v case in our model, in which the innovator's follow-up R&D effort (e.g., targeting other indications) is important in increasing the revenue for the product. Consistent with our results, under the new agreement, Alseres would pay a fixed fee of $7 million to reduce royalties payable to BioAxone from 10%–12% to 4% for nerve repair and 1% for all other indications (*Drug Discovery & Development* 2008). On the contrary, Medivir formed a partnership in February 2010 with Meda Pharmaceutical for Xerese, a cold sore drug. According to the original agreement, Medivir would receive $5 million in fixed payments and a "double-digit" royalty on sale of Xerese in North America. Soon after the launch of Xerese by Meda in the United States, both firms recognized that it will "require considerable marketing resources [from Meda] to achieve successful penetration of this important market" (Medivir 2011). This corresponds to a low v/high λ case in our model in which the marketer's marketing effort is the key to increasing product sales. As a result, the two firms renegotiated their initial agreement in June 2011 to revise Medivir's royalty down to "single-digit" in exchange for a $45 million one-time payment from Meda (Medivir 2011). With a lower royalty payable to Medivir, Meda would have stronger incentive to invest "considerable marketing resources" for Xerese.

As part (iv) of Proposition 4 suggests, if there is no need to have two different royalty rates for the two stages, royalty contract revision obviously would not create any value. The similar observations can be made for the effectiveness coefficient of the marketer's effort m_2, λ. To simplify exposition, we will not provide the details regarding λ in the paper.

Corollary 1. *With symmetric information ($c_h = c_l = c$) under royalty contracts that are not contingent on θ, if $v = 1$ and $\lambda = 1$, royalty revision does not create value for the marketer; i.e., $\Pi^* - \hat{\Pi}^* = 0$.*

Corollary 1 indicates that when the two stages are perfectly balanced in terms of incentive provision for the innovator (i.e., $v = 1$ and $\lambda = 1$), the incentive-realigning effect would be neutralized. Thus, royalty revision would create no value at all for the marketer. When a new factor is added to the model, the above result offers a convenient way of shutting off the incentive-realigning effect so that we can see the pure effect of the newly added factor clearly. We now investigate what effect that asymmetric information would bring into the model.

4.3.3. Information-Revealing Effect. We have identified one positive effect of royalty revision under symmetric information, which enables us to pinpoint how information asymmetry would shape the impact of royalty revision.

Proposition 5. *With asymmetric information on the innovator's cost ($c_h > c_l$) under royalty contracts that are not contingent on θ, (i) if the two stages of the alliance are perfectly balanced—i.e., $v = 1$ and $\lambda = 1$—royalty revision leads to strictly lower expected profit for the marketer; i.e., $\Pi^* - \hat{\Pi}^* < 0$, and $\Pi^* - \hat{\Pi}^*$ is decreasing in $c_h - c_l$. All else being equal, (ii) there exists a threshold $\delta \in (0, \infty)$ such that if $c_h - c_l > \delta$, royalty revision leads to strictly lower expected profit for the marketer (i.e., $\Pi^* < \hat{\Pi}^*$); (iii) there exists a threshold $\tilde{v}$ such that when $v \leq \tilde{v}$, the marketer earns higher expected profit with royalty revision than she does without royalty revision (i.e., $\Pi^* > \hat{\Pi}^*$).*

Part (i) of Proposition 5 says that keeping the two stages perfectly balanced and just making the information asymmetric, would mean royalty revision is harmful to the marketer. This allows us to clearly identify a potential harm of royalty revision, which we call the *information-revealing effect*. With asymmetric information the innovator knows that if he truthfully reveals his type by choosing the contract intended for his type in the initial menu, the marketer will utilize this information in the future contract revision to reduce the innovator's surplus. In contrast, the innovator has no such concern when the royalty will not be revised in the future. As a result, the innovator would be less willing to truthfully

reveal his type under royalty revision than without one. In other words, the possibility of royalty revision hardens the innovator's incentive compatibility in the initial stage, which is reflected by the one extra IC constraint for each type of innovator in model (**P1**) with royalty revision as compared to model (**P2**) without royalty revision. Mathematically, more constraints in model (**P1**) will lead to lower optimal objective function value (the marketer's optimal expected profit). Part (ii) of Proposition 5 shows that when the two types are different enough, the information-revealing effect of the royalty revision will overweigh any potential benefit of the incentive-realigning effect to hurt the marketer's profit.

Empirical research on R&D alliances has long recognized that information asymmetry is prevalent and causes various incentive problems in biopharma alliances (e.g., Lerner 2000, Kim 2011). Pisano (1990) finds that because of uncertainties involved in drug R&D processes, firms in a biopharma alliance usually recognize that "it is futile to lock-in the terms of trade at the outset and generally agree to renegotiate the contract as uncertainties are resolved" (p. 157). He argues that contract renegotiation in biopharma alliances, however, represents a hazardous proposition because one of the parties could try to renegotiate the contract on terms more favorable to itself. Such a concern about the potential of contract renegotiation hurts firms' valuations and incentives to form alliances. Our result on the information-revealing effect voices a similar concern on contract renegotiation as the one argued by Pisano (1990).

With a positive effect (the incentive-realigning effect) and a negative effect (the information-revealing effect), whether royalty revision benefits the marketer or not and the magnitude of its benefit apparently depends on the relative strengths of these two effects. When the positive effect is strong and the negative effect is weak at the same time, royalty revision would most likely lead to higher expected profit for the marketer. According to part (iii) of Proposition 5, this would happen when v takes a small value. Because v is the coefficient of e_2 in the marketing stage, when v is very small the innovator will play a limited role in the marketing stage, no matter what type he is. Consider the extreme case where $v = 0$. Both the high type and the low type would play no role at all in the marketing stage ($ve_2^* = 0$ regardless of e_2^*). Therefore, knowing whether the innovator is a high type or a low type is useless to the marketer. As a result, the innovator would not worry that the marketer will use the information about his type revealed in the first stage, which eliminates the information revealing effect.

Interestingly, when v takes a large value, royalty revision may *not* necessarily benefit the marketer. This is because although a large v does lead to a stronger incentive-realigning effect, it unfortunately leads to a *stronger* information-revealing effect as well. When v is large, the innovator would play an important role in the marketing stage and the marketer would motivate the innovator to exert higher effort. In this case, the difference between the two types of innovator's capabilities would lead to a difference between their efforts e_2^*, which results in a difference between their contributions ve_2^* to the revenue in the marketing stage. So knowing whether it is a high- or low-type innovator involved in the marketing stage is very useful for the marketer. Therefore, the innovator would worry about revealing his type in the first stage, which strengthens the information-revealing effect.

When an R&D alliance has the right characteristics to benefit from royalty revision, managers should clearly establish the expectation of royalty revision in the alliance, for example, by stating the possibility and process of royalty revision in the initial contract negotiations (as in the BMS and ZymoGenetics alliance). However, when an R&D alliance does not benefit from royalty revision, managers should resist the short-term gain of royalty revision and commit not to revise the initial contracts, because ex post contract revision hurts the overall profit in the long run when alliance opportunities with similar characteristics occur repeatedly over time. This can happen especially in alliances where parties can withhold or manipulate critical information. In such cases, managers should clearly commit that contracts will not be changed in the future. For example, they can make the process of contract revision extremely tedious and costly (e.g., requiring detailed reviews, authorizations, and approvals from management at multiple levels) or establish well-defined project categories in which contract revisions were never performed.

5. Royalty Contracts Contingent on θ

In this section, we consider royalty contracts that are contingent on the technical performance θ at the end of the R&D stage. We will call this type of royalty contract a *contingent royalty contract*. Specifically, we consider that the marketer offers a menu of royalty contracts $\{\alpha_{1i}, \alpha_{2i}, t_i\}$, $i \in \{l, h\}$ to the innovator. Under a contract in this menu, the fixed transfer t_i will be made before the R&D takes place. The innovator is promised to receive a payment of $\alpha_{1i}\theta$ at the end of the R&D stage if the R&D outcome is a success with a realized technical performance θ, and to receive a royalty payment of $\alpha_{2i}x$ at the end of the marketing stage. The payment of $\alpha_{1i}\theta$ that is contingent on θ being a technical success can be understood as one form of milestone payment (note that is a fixed milestone payment that is only contingent on the technical

success is a special case) in the alliance. We still focus on separating contracts that induce the innovator with cost coefficient c_i to choose the contract $(\alpha_{1i}, \alpha_{2i}, t_i)$ voluntarily, to truthfully reveal his type, i.

Given that the innovator has chosen the contract $(\alpha_{1i}, \alpha_{2i}, t_i)$, let $\mu_1(i)$ be the marketer's belief of the innovator's type after observing the innovator's contract choice in the R&D stage, and let $\mu_2(i, \theta)$ be the marketer's belief of the innovator's type after observing the realized technical performance θ. Similarly, perfect Bayesian equilibrium requires that beliefs satisfy Bayes' rule, suggesting that $\mu_2(i, \theta) = \mu_1(i) = i$ for $i = \{h, l\}$ and any $\theta \geq 0$.

5.1. Revision of the Initial Royalty Contract
Suppose that the innovator chose the contract $(\alpha_{1i}, \alpha_{2i}, t_i)$ from the initial contract menu to truthfully reveal his type i. If the R&D outcome is a success with a realized θ at the end of the R&D stage, the marketer will pay $\alpha_{1i}\theta$ to the innovator. Then the marketer forms the belief on the innovator's type $\mu_2(i, \theta) = i$ and can propose a revision of the royalty rate α_{2i} to β_i with a fixed transfer γ_i. At this point, the marketer's optimal royalty revision problem and the innovator's acceptance and rejection decisions are the same as the ones under royalty contracts that are not contingent on θ as analyzed in §4.1. Therefore, the marketer's optimal royalty revision strategy is similar to the one characterized in Proposition 1: If the innovator chose the contract $(\alpha_{1i}, \alpha_{2i}, t_i)$ from the initial contract menu and the R&D outcome is a success with a realized θ, it is Pareto improving for the marketer to revise the royalty rate α_{2i} in the initial contract to $\beta_i^* = v^2 c_i / (v^2 c_i + \lambda^2)$ in exchange for a fixed transfer $\gamma_i^*(\theta) = \alpha_{2i}(\theta + \alpha_{2i}v^2 c_i/2 + (1 - \alpha_{2i})\lambda^2) - \beta_i^*(\theta + \beta_i^* v^2 c_i/2 + (1 - \beta_i^*)\lambda^2)$ for $i \in \{l, h\}$.

5.2. Initial Menu of Royalty Contracts
The marketer designs a menu of royalty contracts $\{\alpha_{1i}, \alpha_{2i}, t_i\}$, where $i = \{l, h\}$ such that a type i innovator would voluntarily pick the contract $(\alpha_{1i}, \alpha_{2i}, t_i)$ to truthfully reveal his type, i. The marketer's contract design problem can be formulated and analyzed in a process similar to the one presented in §4.2. The detailed formulation and solution procedure, as well as the optimal contracts, are provided in the appendix. Let $\{\alpha_{1i}^*, \alpha_{2i}^*, t_i^*\}$ for $i \in \{l, h\}$ denote the optimal initial menu of royalty contracts and $\Pi^{\theta*}$ denote the marketer's optimal expected profit under the optimal royalty contracts that are contingent on θ. The following proposition characterizes interesting structures of the optimal initial menu of contingent royalty contracts and conditions under which the marketer should offer to revise the initial royalty rate up or down for the low- and high-type innovators.

PROPOSITION 6. *Under royalty contracts that are contingent on θ, (i) in the optimal initial menu $\{\alpha_{1i}^*, \alpha_{2i}^*, t_i^*\}$ for $i \in \{l, h\}$, the marketer offers $\alpha_{1h}^* = 0$ and $\alpha_{2h}^* > 0$, for the high-type innovator and $\alpha_{1l}^* > 0$ and $\alpha_{2l}^* = 0$ for the low-type innovator; (ii) the marketer always offers the low-type innovator a revising-up contract (i.e., $\beta_l^* > \alpha_{2l}^*$); (iii) if $\lambda \leq v$, the marketer would offer the high-type innovator a revising-up contract (i.e., $\beta_h^* \geq \alpha_{2h}^*$); otherwise, the marketer would offer the high-type innovator a revising-down contract (i.e., $\beta_h^* < \alpha_{2h}^*$).*

Surprisingly, according to part (i), even with the opportunity to write a contingent contract based on θ, the marketer actually would *not* do so for the high-type innovator by setting $\alpha_{1h}^* = 0$ and would only rely on the royalty rate based on the final revenue $\alpha_{2h}^* > 0$ to motivate the innovator's effort in the R&D stage. However, the marketer would do exactly the opposite for the low-type innovator by offering him a contract that is purely contingent on θ (i.e., $\alpha_{1l}^* > 0$) with zero royalty rate $\alpha_{2l}^* = 0$ (which will be revised up to β_l^* later). With the possibility of offering royalty contracts contingent on θ, the marketer has more flexibility in differentiating the two types of innovator by manipulating the additional contract parameter (α_{1i}). Because both α_{1i} and α_{2i} can motivate the innovator's R&D effort, the marketer would fully take advantage of this extra flexibility by using the two extreme structures of α_{1i} and α_{2i} to differentiate. Given the structures of the optimal initial menu, the low-type innovator would always receive a revising-up contract because $\beta_l^* > \alpha_{2l}^* = 0$. This is different from the case for the low type under a noncontingent royalty contract, where she can possibly receive a revising-down contract as well (see part (i) in Proposition 3). For the high-type innovator, the condition for revising up in part (iii) of Proposition 6 is exactly the same as the condition for revising up in part (ii) of Proposition 3. Thus, the marketer's revising up/down strategy for the high-type innovator remains the same under a contingent royalty contract.

5.3. Impact of Royalty Contract Revision
In this section, we will examine the impact of royalty contract revision under royalty contracts that are contingent on θ. We still use a benchmark case in which the marketer offers the innovator a menu of royalty contracts that are contingent on θ, $\{\hat{\alpha}_{1i}, \hat{\alpha}_{2i}, \hat{t}_i\}$ for $i = \{l, h\}$ before the R&D stage takes place, and will *not* revise the royalty rates in the future. Again, this benchmark case is a standard adverse selection problem that can be formulated and solved in procedures similar to the ones presented in §4.3.1 for royalty contracts that are not contingent on θ. The optimal menu of royalty contracts $\{(\hat{\alpha}_{1h}^*, \hat{\alpha}_{2h}^*, \hat{t}_h^*), (\hat{\alpha}_{1l}^*, \hat{\alpha}_{2l}^*, \hat{t}_l^*)\}$ is characterized in the appendix. Let $\hat{\Pi}^{\theta*}$ denote the marketer's optimal expected profit in this benchmark case.

5.3.1. Incentive-Realigning Effect. Similarly, we start with the special cases where the innovator and the marketer have symmetric information (i.e., $c_h = c_l = c$) to characterize the incentive-realigning effect of royalty revision.

PROPOSITION 7. *With symmetric information ($c_h = c_l = c$) under royalty contacts that are contingent on θ, (i) if $v < \lambda$, the marketer offers a royalty contract that is contingent on θ (i.e., $\hat{\alpha}_1^* > 0$ and $\hat{\alpha}_2^* > 0$) and will not revise the contract in the future, and royalty revision creates no value for the marketer; i.e., $\Pi^{\theta*} - \hat{\Pi}^{\theta*} = 0$; (ii) if $v \geq \lambda$, the marketer offers a royalty contract that is not contingent on θ (i.e., $\hat{\alpha}_1^* = 0$ and $\hat{\alpha}_2^* > 0$), and the benefit of royalty revision $\Pi^{\theta*} - \hat{\Pi}^{\theta*}$ is positive and increasing in v.*

Proposition 7 confirms the *incentive-realigning effect* of royalty revision still exists under contingent royalty contracts. Part (i) of the proposition shows that when the effectiveness coefficient of the innovator's R&D effort in the marketing stage v takes smaller values (than λ), the marketer will offer a royalty contract that is contingent on θ and will not propose to revise this contract at the end of the R&D stage. In this case, the need to realign the incentives between the two stages is fully satisfied by the flexible contingent contract structure (which also by nature has two different royalty rates $\hat{\alpha}_1^* > 0$ and $\hat{\alpha}_2^* > 0$) alone. In other words, a contingent royalty contract is perfectly *substitutable* to royalty revision in this scenario, which means royalty revision creates no extra value to the marketer. This is consistent with suggestions made by practitioners that various contingent clauses such as variable royalty rates or take-back clauses can serve as alternatives to contract renegotiation to mitigate incentive-misalignment problems in biopharma alliances (Mason et al. 2008). However, as part (ii) indicates, when v takes larger values, the marketer will *not* offer a contingent royalty contract even though there is an opportunity to do so. As discussed before, when v takes larger values, the marketer should motivate the innovator to exert higher R&D effort in the marketing stage than in the R&D stage. Note that both $\hat{\alpha}_1^*$ and $\hat{\alpha}_2^*$ provide incentives for the innovator's R&D effort in the R&D stage e_1 (through θ and x, respectively). If both $\hat{\alpha}_1^*$ and $\hat{\alpha}_2^*$ are positive, the marketer would provide too much incentive for the innovator's R&D effort e_1 in the R&D stage. Hence, it is optimal for the marketer not to offer a royalty contract contingent on θ by setting $\hat{\alpha}_1^* = 0$, and to rely solely on royalty revision to satisfy the need to realign the incentives between the two stages.

5.3.2. Information-Revealing Effect. We now characterize the information-revealing effect of royalty revision under contingent royalty contracts with asymmetric information.

PROPOSITION 8. *With asymmetric information regarding the innovator's cost ($c_h > c_l$) under royalty contacts that are contingent on θ, (i) if the two stages of the alliance are perfectly balanced—i.e., $v = 1$ and $\lambda = 1$—then royalty revision leads to strictly lower expected profit for the marketer; i.e., $\Pi^{\theta*} - \hat{\Pi}^{\theta*} < 0$, and $\Pi^{\theta*} - \hat{\Pi}^{\theta*}$ is decreasing in $c_h - c_l$; (ii) all else being equal, there exist a threshold $\delta \in (0, \infty)$ such that if $c_h - c_l > \delta$, royalty revision leads to strictly lower expected profit for the marketer (i.e., $\Pi^{\theta*} - \hat{\Pi}^{\theta*} < 0$); (iii) when $v \leq \lambda$, the marketer earns lower expected profit with royalty revision than she does without royalty revision (i.e., $\Pi^{\theta*} < \hat{\Pi}^{\theta*}$).*

Parts (i) and (ii) of Proposition 8 are consistent with their counterparts in Proposition 5 with noncontingent contracts. Part (i) shows that by keeping the two stages perfectly balanced, royalty revision under contingent contracts still hurts the marketer's expected profit, which clearly verifies that the robustness of the information-revealing effect of royalty revision under contingent royalty contract. Part (ii) further verifies that how the strength of the information-revealing effect of the royalty revision varies with the difference between the two innovator types is also robust to the contingent contract structure.

Part (iii) of Proposition 8 is in sharp contrast to its counterpart, part (iii) in Proposition 5, which shows that when v takes a small enough value, the marketer earns *higher* expected profit with royalty revision than she does without royalty revision (i.e., $\Pi^* > \hat{\Pi}^*$) under a noncontingent royalty contract. As discussed after Proposition 5, a smaller v would lead to a stronger incentive-realigning effect and weaker information-revealing effect at the same time, which makes royalty revision more beneficial to the marketer under a noncontingent royalty contract. The first part of this statement on the stronger incentive-realigning effect would not be true anymore under a contingent royalty contract. According to part (i) of Proposition 7, when v takes smaller values than λ, the incentive-realigning effect of royalty revision would be fully captured by the flexible contingent contract structure. Therefore, when v takes smaller values than λ under a contingent royalty contract, the marketer earns *lower* expected profit with royalty revision than she does without royalty revision. The following result summarizes the impact of the opportunity of writing contingent royalty contracts on the value of royalty revision.

PROPOSITION 9. *With asymmetric information regarding the innovator's cost ($c_h > c_l$), (i) when $v \leq \lambda$, the marketer earns the highest expected profit by offering a royalty contract that is contingent on θ without royalty revision (i.e., $\hat{\Pi}^{\theta*} \geq \max\{\Pi^{\theta*}, \Pi^*, \hat{\Pi}^*\}$); (ii) when $v > \lambda$, writing a royalty contract that is contingent on θ weakens the information-revealing effect of royalty revision, which in turn enhances the value of royalty revision for the marketer (i.e., $\Pi^{\theta*} - \hat{\Pi}^{\theta*} \geq \Pi^* - \hat{\Pi}^*$).*

The marketer has four possible contracting strategies: contingent with or without revision (studied in this section) and noncontingent with or without revision (studied in the previous section). Part (i) of Proposition 9 says that when v takes smaller values (than λ), the best choice for the marketer is to offer royalty contracts that are contingent on θ without revision. All else being equal, a contingent contract in general would do no worse than a noncontingent contract because of its flexibility. Then for $v \leq \lambda$, recall that part (i) of Proposition 7 implies that a contingent contract structure and royalty revision are perfectly substitutable in terms of incentive realignment. Together with part (iii) of Proposition 8, it implies that royalty revision leads to a net loss for the marketer when $v \leq \lambda$ and therefore should be avoided. This result indicates that if the innovator does not play a significant role in the marketing stage, the marketer should try to identify a verifiable outcome (such as θ) of the R&D stage and simply associate the innovator's payoff to that outcome by offering a contingent contract to avoid the complications of contract revision.

Surprisingly, part (ii) of Proposition 9 tells a very different story between contingent contracts and royalty revision. When $v > \lambda$, on one hand, as indicated by part (ii) of Proposition 7, a contingent contract cannot capture the incentive-realigning benefit of royalty revision because of concerns on overincentivizing the innovator's R&D effort e_1. On the other hand, the more flexible contingent contract structure helps weaken the negative information-revealing effect of royalty revision because, as discussed after Proposition 6, the contingent contract structure itself provides more flexibility for the marketer to differentiate different types of innovator. As a result, using contingent contracts enhances the value of royalty revision. Thus, a contingent royalty contract is *complementary* to royalty revision. This implies that if the innovator plays a significant role in the marketing stage, the marketer should try to jointly use a contingent contract (if possible) and royalty revision to improve her profit. This is consistent with findings in existing literature that performance contingent payments such as milestone payment (Kim 2011) and options (Nöldeke and Schmidt 1995) can mitigate information asymmetry problems.

6. Extensions
The model we developed in this paper offers a convenient and flexible framework to incorporate more complex factors. In this section, we discuss several interesting extensions of the model.

6.1. Alliance Termination After Success
If the marketer incurs a continuation cost $K > 0$ in the marketing stage, she could decide to terminate the alliance when θ is not high enough for her expected profit from the marketing stage to recover K. The possibility of alliance termination after success would make royalty contract revision more beneficial to the marketer. First, with alliance termination, the innovator is more likely to accept a revised royalty rate proposed by the marketer because he fears the possibility of termination if he rejects the proposal. Second, royalty revision could avoid inefficient termination. Without royalty revision, the alliance will be terminated as long as continuation with the initial royalty rate is not able to recover K. However, it is possible that the innovator's expected profit is positive if the alliance can be continued. With royalty revision, the alliance could work out a new royalty rate to reallocate the potential gains from continuation so that both the innovator and the marketer could have positive payoffs instead of zeros under termination. A formal analysis of this extension is provided in Xiao and Xu (2011).

6.2. Risk-Averse Innovator
With a risk-averse innovator, royalty contract revision creates one more benefit to the marketer, which we call the *risk-reallocation effect*. After the R&D stage is completed, the technical risk or uncertainty would be resolved and the total risk to which the alliance is exposed is reduced. Therefore, there is a need for the alliance to revise the initial royalty contract to reallocate the amount of risk that will be borne by each party in the marketing stage. Royalty revision provides a natural way for the marketer to offer two different royalty rates in the two stages, respectively, to allocate the risks. A formal model of the risk-reallocation effect of royalty revision with a risk-averse innovator is provided in Xiao and Xu (2011).

6.3. Innovator Designs and Offers Contracts
It is possible that the innovator could take the lead to design and offer contracts to the marketer (see Crama et al. 2008). If we flip the roles of the innovator and the marketer as well as the information structure so the innovator offers contracts and the marketer has private information, our analysis and results would carry through from the perspective of the innovator. However, if we flip the roles of the two parties but keep the information structure unchanged, so the innovator offers contracts and has private information, the model would become a signaling model with contract revision. The solution process and the insight would be very different from the ones presented in this paper. This extension is certainly very interesting, but would deserve a separate paper.

7. Conclusion
In a strategic R&D alliance, firms often revise a pre-agreed royalty contract as the alliance progresses.

This paper studies how and when to revise royalty contract in a multistage R&D alliance (an R&D stage followed by a marketing stage) consisting of an innovator and a marketer. The marketer takes the lead to offer royalty contracts to the innovator and could propose to revise the royalty contract chosen by the innovator after the R&D stage. With the potential for royalty revision, the marketer not only needs to ensure that the innovator chooses the right initial contract, but also needs to ensure that he accepts the revised royalty contract later. We show that this leads to more severe distortions in the optimal initial royalty contracts. If the innovator plays a significant role in the marketing stage, the marketer should offer a low royalty rate initially and then propose to revise the royalty rate up later. Otherwise, she should do the opposite by offering a high royalty rate initially and then propose to revise the royalty rate down later.

We characterize two fundamental effects of royalty revision in an R&D alliance: the incentive-realigning effect and the information-revealing effect. Royalty revision provides the marketer with an important flexibility to dynamically adjust royalty rates according to the innovator's contributions in different stages of the alliance, to better align his incentives. This incentive-realigning effect improves the marketer's expected profit from the alliance. However, royalty revision makes it harder for the marketer to obtain private information from the innovator because the innovator worries that the marketer will take advantage of the information to revise the initial contract to a more favorable contract for herself later. This information-revealing effect hurts the marketer's expected profit. Therefore, although royalty revision is ex post Pareto improving for both parties in an alliance, it is a double-edged sword for the marketer. Whether royalty revision would benefit the marketer or not depends on the relative strength of these two effects. In an alliance where the innovator's contributions to the alliance are very imbalanced in the two stages so that two very different royalty rates are needed to align his incentives accordingly, the incentive-realigning effect would be strong and the marketer should clearly establish the expectation for royalty revision. In contrast, in an alliance where parties can withhold or manipulate critical information, the information-revealing effect of royalty revision would be strong. In such a case, the marketer should resist the short-term gain of royalty revision and establish credible commitment that contracts will not be revised in the future (e.g., by making the renegotiation process tedious and costly, or by establishing project categories in which contract revisions were never performed).

It is possible to use a contingent royalty contract that offers intermediate payment contingent on the technical performance of the R&D stage in a multistage alliance. The contingent payment provides the marketer with more flexibility. This flexibility can be perfectly substitutable to the flexibility of royalty revision if the innovator does not contribute significantly in the marketing stage. In this case, managers could either use a contingent royalty contract or practice royalty revision, whichever is more convenient. If the innovator does contribute significantly in the marketing stage, we find that a contingent royalty contract is complementary to and enhances the benefit of royalty revision. Thus, managers should use a contingent contract (if possible) in combination with royalty revision to improve profits.

Our results offer interesting, testable predictions/ hypotheses, especially in the biopharma context. For example, the information-revealing effect implies that royalty revision is more likely to be performed in alliances where partners have collaborated in the past, so they know sufficient information about each other. The discussions of Proposition 3 suggest that revising royalties up is more likely to happen in an alliance with a niche drug, whereas revising royalties down is more likely to happen in an alliance with a blockbuster drug. With increasing availability of data on R&D alliances, especially biopharma alliances (e.g., Deloitte LLP publishes data on publicly announced alliances in biotech industry), it is possible to empirically test these predictions/hypotheses. Another interesting future research is to extend our one-dimensional static R&D model to more complex R&D settings such as an open-ended search (Sommer and Loch 2004) in a dynamic evolving environment (Jain and Ramdas 2005) with multidimensional performance measures (e.g., Chao and Kavadias 2008). We have focused on separating contracts. Analyzing semiseparating and pooling contracts and comparing them with separating contracts would be interesting future research. In a pooling contract, the marketer offers a single royalty contract initially (which avoids the information-revealing effect of separating contracts). After observing θ after the R&D stage, she may update her prior belief about the innovator's type and then could propose to revise the initial contract.

Acknowledgments

Appendix

Proof of Proposition 1

Because the objective function of the marketer's contract revision problem decreases in γ_i and the constraint is

relaxed as γ_i increases, the constraint must be binding at the optimal solution; i.e.,

$$\gamma_i = \alpha_i\left(\theta + \frac{\alpha_i v^2 c_i}{2} + (1-\alpha_i)\lambda^2\right)$$
$$- \beta_i\left(\theta + \frac{\beta_i v^2 c_i}{2} + (1-\beta_i)\lambda^2\right). \qquad (9)$$

Substituting γ_i with the right-hand side of the above equation, we can rewrite the objective function as a concave quadratic function of β_i, which is maximized at

$$\beta_i^* = \frac{v^2 c_i}{v^2 c_i + \lambda^2}.$$

This, together with (9), determines $\gamma_i^*(\theta)$.

Proof of Proposition 2
We first derive the closed form expressions for $\pi_r(i,j)$ and $\pi_a(i,j)$. Recall that

$$\pi_r(i,j) = \max_{e_1\geq 0, e_2\geq 0}\left\{s\left[\alpha_j(e_1+m_1+ve_2+\lambda m_2) - \frac{e_2^2}{2c_i}\right] - \frac{e_1^2}{2c_i} + t_j\right\}$$
$$= s\alpha_j\left[\frac{\alpha_j s c_i}{2} + \frac{\alpha_j v^2 c_i}{2} + (1-\alpha_j)(s+\lambda^2)\right] + t_j, \qquad (10)$$

because the marketer would exert R&D effort $m_1 = (1-\alpha_j)s$ and marketing effort $m_2 = (1-\alpha_j)\lambda$.

Given the contract choice j and the technical performance θ after a technical success, the type i innovator's expected profit in the second stage (excluding the sunk effort cost associated with e_1 and the fixed transfer t) under the revised contract is $\beta_j^*(\theta + ve_2 + \lambda m_2) + \gamma_j^*(\theta) - e_2^2/2c_i$, which implies that $e_2^* = \beta_j^* vc_i$. Note that the marketer would exert marketing effort $m_2^* = (1-\beta_j^*)\lambda$. Therefore,

$$\pi_a(i,j) = \max_{e_1\geq 0}\left\{s\left[\alpha_j\left(e_1+m_1+\frac{\alpha_j v^2 c_j}{2} + (1-\alpha_j)\lambda^2\right)\right.\right.$$
$$\left.+ \frac{v^2\beta_j^{*2}(c_i-c_j)}{2}\right] - \frac{e_1^2}{2c_i} + t_j\right\}$$
$$= s\alpha_j\left[\frac{\alpha_j s c_i}{2} + \frac{\alpha_j v^2 c_j}{2} + (1-\alpha_j)(s+\lambda^2)\right]$$
$$+ \frac{sv^2\beta_j^{*2}(c_i-c_j)}{2} + t_j, \qquad (11)$$

where the second equality is due to $m_1 = (1-\alpha_j)s$ and $e_1 = \alpha_j s c_i$.

We make the following observations to simplify (**P1**). First, because $\pi_a(h,l) \geq \pi(l,l)$, (IRh) can be inferred by (IRl) and (ICh–a). Thus, (IRh) can be ignored from (**P1**). Second, (IRl) must be binding at the optimal solution, because otherwise decreasing t_l improves the objective value without violating any constraint. The binding (IRl), together with (11) when $i=j=l$, leads to

$$t_l = -s\alpha_l\left(\frac{\alpha_l s c_l}{2} + \frac{\alpha_l v^2 c_l}{2} + (1-\alpha_l)(s+\lambda^2)\right). \qquad (12)$$

Third, either (ICh–r) or (ICh–a) must be binding at the optimal solution, because otherwise decreasing t_h improves the

objective value without violating any constraint. It follows from (10) and (11) with $i=h$ and $j=l$ that

$$\pi_a(h,l) = \pi_r(h,l) + \frac{sv^2}{2}(\beta_l^{*2} - \alpha_l^2)(c_h - c_l).$$

Therefore, (ICh–r) is binding and (ICh–a) is redundant if $\alpha_l \geq \beta_l^*$; otherwise, (ICh–a) is binding and (ICh–r) is redundant.

According to the third observation, we decompose (**P1**) into two subproblems by imposing the constraint $\alpha_l \geq \beta_l^*$ ($\alpha_l \leq \beta_l^*$) to (**P1**). With the new constraint $\alpha_l \geq \beta_l^*$, (ICh–r) is binding; i.e., $\pi(h,h) = \pi_r(h,l)$. This, together with (10) and (11), leads to

$$t_h = -s\alpha_h\left(\frac{\alpha_h s c_h}{2} + \frac{\alpha_h v^2 c_h}{2} + (1-\alpha_h)(s+\lambda^2)\right)$$
$$+ \frac{s\alpha_l^2}{2}(s+v^2)(c_h-c_l). \qquad (13)$$

Substituting t_l and t_h with the right-hand side of (12) and (13) into the objective function and the constraints of (**P1**), we have the first subproblem, denoted by (**P1′**),

(**P1′**)

$$\max_{\alpha_h,\alpha_l}\left\{\frac{s(s+\lambda^2)}{2} + \rho s[\Gamma(sc_h, sc_h+s, \alpha_h) + \Gamma(v^2 c_h, v^2 c_h+\lambda^2, \beta_h^*)]\right.$$
$$+ (1-\rho)s\left[\Gamma\left(sc_l, sc_l+s+\frac{\rho}{1-\rho}(s+v^2)(c_h-c_l), \alpha_l\right)\right.$$
$$\left.\left.+ \Gamma(v^2 c_l, v^2 c_l+\lambda^2, \beta_l^*)\right]\right\}$$

s.t. $\quad \alpha_h \geq \alpha_l,$ (ICl–r)
$\quad\quad s\alpha_h^2 + v^2\beta_h^{*2} \geq (s+v^2)\alpha_l^2,$ (ICl–a)
$\quad\quad \alpha_l \geq \beta_l^*,$

where $\Gamma(A,B,x) \equiv Ax - (B/2)x^2$. Similarly, by adding the new constraint $\alpha_l \leq \beta_l^*$, we have the second subproblem, denoted by (**P1″**):

(**P1″**)

$$\max_{\alpha_h,\alpha_l}\left\{\frac{s(s+\lambda^2)}{2} + \rho s[\Gamma(sc_h, sc_h+s, \alpha_h) + \Gamma(v^2 c_h, v^2 c_h+\lambda^2, \beta_h^*)]\right.$$
$$+ (1-\rho)s\left[\Gamma\left(sc_l, sc_l+s+\frac{s\rho}{1-\rho}(c_h-c_l), \alpha_l\right)\right.$$
$$\left.\left.+ \Gamma\left(v^2 c_l, v^2 c_l+\lambda^2+\frac{\rho}{1-\rho}(c_h-c_l)v^2, \beta_l^*\right)\right]\right\}$$

s.t. $\quad (s+v^2)\alpha_h^2 \geq s\alpha_l^2 + v^2\beta_l^{*2},$ (ICl–r)
$\quad\quad s\alpha_h^2 + \beta_h^{*2}v^2 \geq s\alpha_l^2 + \beta_l^{*2}v^2,$ (ICl–a)
$\quad\quad \alpha_l \leq \beta_l^*.$

Let Π_1^* and Π_2^* be the optimal objective value of (**P1′**) and (**P1″**), respectively. Then the optimal solution to (**P1′**) (**P1″**) is also optimal to the original problem if and only if $\Pi_1^* \geq \Pi_2^*$ ($\Pi_1^* \leq \Pi_2^*$). Next, we make two claims that characterize conditions under which $\Pi_1^* \geq \Pi_2^*$ and $\Pi_1^* \leq \Pi_2^*$, respectively.

CLAIM 1. $\Pi_1^* \geq \Pi_2^*$ *if* $\beta_l^* \leq \alpha_2$.

PROOF OF CLAIM 1. Note that $\alpha_h = \alpha_1$ and $\alpha_l = \alpha_2$ maximize the objective function of (**P1″**). Thus, if $\beta_l^* \leq \alpha_2$, then the optimal solution to (**P1″**) is $\alpha_h = \alpha_1$ and $\alpha_l = \beta_l^*$. This is also a feasible solution to (**P1′**), yielding the same objective value in both (**P1′**) and (**P1″**). Hence, $\Pi_1^* \geq \Pi_2^*$.

CLAIM 2. $\Pi_1^* \leq \Pi_2^*$ *if* $\beta_l^* \geq \alpha_3$.

PROOF OF CLAIM 2. Note that $\alpha_h = \alpha_1$ and $\alpha_l = \alpha_3$ maximize the objective function of (**P1′**). Thus, if $\beta_l^* \geq \alpha_3$, then the optimal solution to (**P1′**) is $\alpha_h = \alpha_1$ and $\alpha_l = \beta_l^*$. This is also a feasible solution to (**P1″**), yielding the same objective value in both (**P1′**) and (**P1″**). Hence, $\Pi_2^* \geq \Pi_1^*$.

Finally, we are ready to characterize the optimal solution to (**P1**) in five mutually exclusive cases (listed in the table in Proposition 2).

Case 1: $\beta_h^{*2} \leq \varpi_2$. In this case, because $\varpi_2 \leq \alpha_3^2$ and $\beta_l^* \leq \beta_h^*$, we have $\beta_l^* \leq \alpha_3$. This also implies that $\beta_l^* \leq \alpha_2$, which by Claim 1 suggests that the optimal solution to (**P1′**) is also optimal to (**P1**). Thus, it suffices to solve (**P1′**). Note that the unconstrained optimal solution to (**P1′**), $\alpha_h = \alpha_1$ and $\alpha_l = \alpha_3$, satisfies the first and third constraint of (**P1′**) but violates the second constraint, i.e., (IC*l*–r). Hence, (IC*l*–r) of (**P1′**) must be binding at the optimal solution. Furthermore, (IC*l*–a) of (**P1′**) can be ignored. Thus, (**P1′**) can be simplified to

$$\max_{\alpha_l \geq \beta_l^*} \left\{ \frac{s(s+\lambda^2)}{2} + \rho s \left[\Gamma(sc_h, sc_h+s, \alpha_h) + \Gamma(v^2 c_h, v^2 c_h + \lambda^2, \beta_h^*) \right] \right.$$
$$+ (1-\rho)s \left[\Gamma\left(sc_l, sc_l+s+\frac{\rho}{1-\rho}(s+v^2)(c_h-c_l), \alpha_l\right) \right.$$
$$\left. \left. + \Gamma(v^2 c_l, v^2 c_l + \lambda^2, \beta_l^*) \right] \right\},$$

where α_h can be determined by α_l according to the binding (IC*l*–r) constraint: $s\alpha_h^2 + \beta_h^{*2} v^2 = \alpha_l^2(s+v^2)$. This can be solved by a simple one-dimensional search over α_l. Thus, in this case, $\beta_l^* \leq \alpha_l^* \leq \alpha_3$, $\alpha_h^* \geq \alpha_1$.

Case 2: $\beta_l^* \leq \alpha_3$, $\beta_h^{*2} > \varpi_2$. In this case, $\beta_l^* \leq a_3 \leq a_2$, which by Claim 1 suggests that it suffices to solve (**P1′**). Note that the solution, $\alpha_h = \alpha_1$ and $\alpha_l = \alpha_3$, maximizes the objective function of (**P1′**) and satisfies all the constraints of (**P1′**), and thus it is an optimal solution to (**P1′**). Thus, in this case, $\alpha_h^* = \alpha_1$ and $\alpha_l^* = \alpha_3$.

Case 3: $\alpha_3 < \beta_l^* \leq \alpha_2$. It follows from Claims 1 and 2 that $\Pi_1^* = \Pi_2^*$; further, the solution, $\alpha_h = \alpha_1$ and $\alpha_l = \beta_l^*$, is an optimal solution to (**P1′**). Thus, in this case, $\alpha_h^* = \alpha_1$ and $\alpha_l^* = \beta_l^*$.

Similarly, in Cases 4 and 5, it suffices to solve (**P1″**). The rest of the proof is analogous to that of Cases 1 and 2 and is thus omitted.

Proof of Proposition 3

Part (i) follows directly from Proposition 2, where $\beta_l^* \geq \alpha_l^*$ if and only $\beta_l^* \geq \alpha_3$, which leads to the condition in part (i) after collecting terms. Next we prove part (ii). If $v^2 c_h/(v^2 c_h + \lambda^2) \geq c_h/(c_h + 1)$ or equivalently $\lambda \leq v$, which implies $\beta_h^* \geq \alpha_1$, then the optimal solution falls into Cases 2–5. In Cases 2–4, $\beta_h^* \geq \alpha_h^*$ because $\alpha_h^* = \alpha_1$. In Case 5, (IC*l*–r) is binding, suggesting that $\alpha_h^* \leq \beta_h^*$ and hence $\beta_h^* \geq \alpha_h^*$. If $\beta_h^* < \alpha_1$, then $\beta_h^* < \alpha_h^*$ because $\alpha_h^* \geq \alpha_1$ in all the five cases.

The Optimal Solution to (P2)

We perform the following steps to simplify (**P2**). First, (IR*h*) can be inferred by (IR*l*) and (IC*h*) and thus can be ignored. Second, (IR*l*) must be binding at the optimal solution because otherwise decreasing $\hat{t}_l$ improves the objective value without violating any constraint. Third, (IC*h*) must be binding at the optimal solution because otherwise decreasing $\hat{t}_h$ improves the objective value without violating any constraint. The binding (IR*l*) and (IC*h*) constraints lead to

$$\hat{t}_l = -s\hat{\alpha}_l \left(\frac{s\hat{\alpha}_l c_l}{2} + \frac{v^2 \hat{\alpha}_l c_l}{2} + (1-\hat{\alpha}_l)(s+\lambda^2) \right) \quad (14)$$

and

$$\hat{t}_h = -s\hat{\alpha}_h \left(\frac{s\hat{\alpha}_h c_h}{2} + \frac{v^2 \hat{\alpha}_h c_h}{2} + (1-\hat{\alpha}_h)(s+\lambda^2) \right)$$
$$+ \frac{s\hat{\alpha}_l^2}{2}(s+v^2)(c_h - c_l). \quad (15)$$

We ignore (IC*l*) for the moment and solve the relaxed problem. Substituting $\hat{t}_l$ and $\hat{t}_h$ with the right-hand side of (14) and (15), respectively, we can rewrite the objective function of (**P2**) as follows:

$$\max_{\hat{\alpha}_h, \hat{\alpha}_l} \left\{ \frac{s(s+\lambda^2)}{2} + \rho s\Gamma(c_h(s+v^2), c_h(s+v^2)+s+\lambda^2, \hat{\alpha}_h) \right.$$
$$+ (1-\rho)s\Gamma\left(c_l(s+v^2), c_l(s+v^2)+s+\lambda^2 \right.$$
$$\left. \left. + \frac{\rho}{1-\rho}(s+v^2)(c_h-c_l), \hat{\alpha}_l \right) \right\}, \quad (16)$$

which is a separate concave quadratic function of $\hat{\alpha}_l$ and $\hat{\alpha}_h$. Let $\hat{\alpha}_h^*$ and $\hat{\alpha}_l^*$ be the maximizer of the above two concave functions, respectively. This, together with (14) and (15), determines $\hat{t}_h^*$ and $\hat{t}_l^*$. It is straightforward to verify that under this solution, (IC*l*) is satisfied. Thus, the above solution is also optimal to (**P2**).

Proof of Proposition 4

(i) Define $\Gamma(A, B) \equiv \max_{x \geq 0}\{Ax - (B/2)x^2\}$. Suppose $c_h = c_l = c$. Recall that $\Pi^* = \max\{\Pi_1^*, \Pi_2^*\}$, where Π_1^* and Π_2^* are the optimal value of (**P1′**) and (**P1″**), respectively. When $c_h = c_l = c$, it is straightforward to solve (**P1′**) and (**P1″**), resulting in

$$\Pi^* = \frac{s(s+\lambda^2)}{2} + s\Gamma(sc, sc+s) + s\Gamma(v^2 c, v^2 c + \lambda^2). \quad (17)$$

Further, it follows from (16) that

$$\hat{\Pi}^* = \frac{s(s+\lambda^2)}{2} + s\Gamma(c(s+v^2), c(s+v^2)+s+\lambda^2). \quad (18)$$

By comparing (17) and (18), it follows from the definition of $\Gamma(\cdot, \cdot)$ that $\Pi^* \geq \hat{\Pi}^*$.

Taking the derivative of $\Pi^* - \hat{\Pi}^*$ given in (17) and (18) with respect to v, we have $d(\Pi^* - \hat{\Pi}^*)/dv = 2svc[\beta^* - \beta^{*2}/2 - (\hat{\alpha}^* - \hat{\alpha}^{*2}/2)]$. Because $\beta^* \leq 1$ and $\hat{\alpha}^* \leq 1$, the sign of $d(\Pi^* - \hat{\Pi}^*)/dv$ is the same as that of $\beta^* - \hat{\alpha}^*$. It follows from the definition $\alpha^* = c/(c+1)$, $\beta^* = v^2 c/(v^2 c + \lambda^2)$, and $\hat{\alpha}^* = c(s+v^2)/(c(s+v^2)+s+\lambda^2)$ that $\hat{\alpha}^*$ is always between α^* and β^*. Thus, the sign of $\beta^* - \hat{\alpha}^*$ is the same as that of $\beta^* - \alpha^*$. Clearly, there exists a threshold $\bar{v} \in [0, \infty)$ that (ii) for $v < \bar{v}$, $\alpha^* > \beta^*$ and thus $d(\Pi^* - \hat{\Pi}^*)/dv < 0$, which, together with Proposition 5, suggests that $\Pi^* - \hat{\Pi}^*$ is strictly positive and decreasing in v. (iii) For $v > \bar{v}$, $\alpha^* < \beta^*$, and

thus $d(\Pi^* - \hat{\Pi}^*)/dv > 0$, which, together with Proposition 5, suggests that $\Pi^* - \hat{\Pi}^*$ is strictly positive and increasing in v. (iv) For $v = \bar{v}$, $\alpha^* = \beta^*$ and $\Pi^* = \hat{\Pi}^*$.

Proof of Corollary 1
The result follows directly from (17) and (18).

Proof of Proposition 5
(i) Suppose $v = 1$ and $\lambda = 1$. By definition, $\alpha_2 < \beta_l^* \leq \varpi_1$. This, together with Proposition 2, implies that

$$\Pi^* = \frac{s(s+\lambda^2)}{2} + s(s+1)\rho\Gamma(c_h, c_h + 1)$$
$$+ (1-\rho)s\left[\Gamma\left(sc_l, sc_l + s + \frac{\rho s}{1-\rho}(c_h - c_l)\right)\right.$$
$$\left. + \Gamma\left(c_l, c_l + 1 + \frac{\rho}{1-\rho}(c_h - c_l), \beta_l^*\right)\right],$$

where $\beta_l^* = c_l/(c_l + 1)$, $\Gamma(A, B) \equiv \max_{x \geq 0}\{Ax - (B/2)x^2\}$, and $\Gamma(A, B, x) \equiv Ax - (B/2)x^2$. By (16),

$$\hat{\Pi}^* = \frac{s(s+\lambda^2)}{2} + s(s+1)\rho\Gamma(c_h, c_h + 1)$$
$$+ s(s+1)(1-\rho)\Gamma\left(c_l, c_l + 1 + \frac{\rho}{1-\rho}(c_h - c_l)\right).$$

Hence, the above two equations lead to

$$\Pi^* - \hat{\Pi}^* = (1-\rho)s\left[\Gamma\left(c_l, c_l + 1 + \frac{\rho}{1-\rho}(c_h - c_l), \beta_l^*\right)\right.$$
$$\left. - \Gamma\left(c_l, c_l + 1 + \frac{\rho}{1-\rho}(c_h - c_l)\right)\right]$$
$$\leq 0,$$

where the equality holds if $c_h = c_l$. Further, fixing c_l and letting $\Delta = c_h - c_l$ vary, we have $d(\Pi^* - \hat{\Pi}^*)/d\Delta = (1-\rho)s(\rho/(1-\rho))(\alpha_l^{*2}/2 - \beta_l^{*2}/2)$, where $\alpha_l^* = c_l/(c_l + 1 + (\rho/(1-\rho))\Delta) < \beta_l^*$ for $\Delta > 0$. Hence, $d(\Pi^* - \hat{\Pi}^*)/d\Delta < 0$ for $\Delta > 0$. (ii) Suppose $c_h = +\infty$. Then $\alpha_2 = \alpha_3 = 0$, and thus Π^* is equal to the optimal objective value of (**P1″**) defined in the proof of Proposition 2. Because $\beta_l^* > 0$, it follows from the objective function of (**P1″**) that $\Pi^* = -\infty$. Thus, as c_h is sufficiently large, $\Pi^* < \hat{\Pi}^*$. Therefore, there exist a threshold $\delta \in (0, \infty)$ such that if $c_h - c_l > \delta$, $\Pi^* - \hat{\Pi}^* < 0$. (iii) Suppose $v = 0$. Then $\beta_l^* = \beta_h^* = 0$, and thus Π^* is equal to the optimal objective value of (**P1′**) defined in the proof of Proposition 2. Further, the optimal solution to (**P1′**) is the unconstrained optimum: $\alpha_h^* = \alpha_1$ and $\alpha_l^* = \alpha_3$. Hence,

$$\Pi^* = \frac{s(s+\lambda^2)}{2} + \rho s\Gamma(sc_h, sc_h + s)$$
$$+ (1-\rho)s\Gamma\left(sc_l, sc_l + s + \frac{\rho s}{1-\rho}(c_h - c_l)\right).$$

Recall from (16) that when $v = 0$,

$$\hat{\Pi}^* = \frac{s(s+\lambda^2)}{2} + \rho s\Gamma(sc_h, sc_h + s + \lambda^2)$$
$$+ (1-\rho)s\Gamma\left(sc_l, sc_l + s + \lambda^2 + \frac{\rho s}{1-\rho}(c_h - c_l)\right).$$

The above two equations, together with the definition of $\Gamma(A, B)$ and $\Gamma(A, B, x)$, lead to $\Pi^* > \hat{\Pi}^*$. This implies that there exists a threshold $\tilde{v}$ when $v \leq \tilde{v}$, $\Pi^* > \hat{\Pi}^*$.

The Optimal Contingent Royalty Contracts with Revision and Proof of Proposition 6
Let $\pi_r(i, j)$ $(\pi_a(i, j))$ be the type i innovator's expected profit by choosing contract j in the first stage and rejecting (accepting) the royalty revision in the second stage. Next we present the closed form expressions for $\pi_r(i, j)$ and $\pi_a(i, j)$ (the reasonings are similar to those in the proof of Proposition 2 and thus omitted for simplicity):

$$\pi_r(i, j) = s\left[(\alpha_{1j} + \alpha_{2j})\left(\frac{(\alpha_{1j} + \alpha_{2j})sc_i}{2} + (1 - \alpha_{1j} - \alpha_{2j})s\right)\right.$$
$$\left. + \alpha_{2j}\left(\frac{\alpha_{2j}v^2c_i}{2} + (1 - \alpha_{2j})\lambda^2\right)\right] + t_j,$$

and

$$\pi_a(i, j) = s\left[(\alpha_{1j} + \alpha_{2j})\left(\frac{(\alpha_{1j} + \alpha_{2j})sc_i}{2} + (1 - \alpha_{1j} - \alpha_{2j})s\right)\right.$$
$$\left. + \alpha_{2j}\left(\frac{\alpha_{2j}v^2c_j}{2} + (1 - \alpha_{2j})\lambda^2\right)\right]$$
$$+ \frac{sv^2\beta_j^{*2}(c_i - c_j)}{2} + t_j.$$

The marketer's expected profit when the type i innovator truthfully reveals his type is given as

$$\Pi(i, i) = s\left[(1 - \alpha_{1i} - \alpha_{2i})\left((\alpha_{1i} + \alpha_{2i})sc_i + \frac{(1 - \alpha_{1i} - \alpha_{2i})s}{2}\right)\right.$$
$$- \alpha_{2i}\left(\frac{\alpha_{2i}v^2c_i}{2} + (1 - \alpha_{2i})\lambda^2\right) + \frac{\lambda^2}{2} + v^2c_i\beta_i^*$$
$$\left. - \frac{(v^2c_i + \lambda^2)}{2}\beta_i^{*2}\right] - t_i.$$

The marketer's initial contract design problem, denoted by (**P3**), is the same as (**P1**), which we do not repeat here. The solution procedure is similar. First, (IRh) can be ignored from (**P3**). Second, (IRl) must be binding at the optimal solution. The binding (IRl) leads to

$$t_l = -s\left[(\alpha_{1l} + \alpha_{2l})\left(\frac{(\alpha_{1l} + \alpha_{2l})sc_l}{2} + (1 - \alpha_{1l} - \alpha_{2l})s\right)\right.$$
$$\left. + \alpha_{2l}\left(\frac{\alpha_{2l}v^2c_l}{2} + (1 - \alpha_{2l})\lambda^2\right)\right].$$

Third, either (ICh–r) or (ICh–a) must be binding at the optimal solution, which leads to

$$t_h = -s\left[(\alpha_{1h} + \alpha_{2h})\left(\frac{(\alpha_{1h} + \alpha_{2h})sc_h}{2} + (1 - \alpha_{1h} - \alpha_{2h})s\right)\right.$$
$$\left. + \alpha_{2h}\left(\frac{\alpha_{2h}v^2c_h}{2} + (1 - \alpha_{2h})\lambda^2\right)\right]$$
$$+ \frac{s(c_h - c_l)}{2}(s(\alpha_{1l} + \alpha_{2l})^2 + v^2\max(\alpha_{2l}^2, \beta_l^{*2})).$$

Consequently, we can simplify (**P3**) as follows:

(**P3**)

$$\max_{\alpha_{1h}, \alpha_{2h}, \alpha_{1l}, \alpha_{2l}} \left\{\frac{s(s+\lambda^2)}{2} + \rho s\left[\Gamma(sc_h, sc_h + s, \alpha_{1h} + \alpha_{2h})\right.\right.$$
$$\left.\left. + \Gamma(v^2c_h, v^2c_h + \lambda^2, \beta_h^*)\right]\right.$$

$$+(1-\rho)s\left[\Gamma\left(sc_l, sc_l+s+\frac{\rho}{1-\rho}s(c_h-c_l), \alpha_{1l}+\alpha_{2l}\right)\right.$$

$$+\Gamma(v^2c_l, v^2c_l+\lambda^2, \beta_l^*)$$

$$\left.\left.-\frac{\rho}{1-\rho}\frac{(c_h-c_l)v^2}{2}\max(\alpha_{2l}^2, \beta_l^{*2})\right]\right\}$$

s.t. $[s(\alpha_{1h}+\alpha_{2h})^2+v^2\alpha_{2h}^2](c_h-c_l)$

$$\geq [s(\alpha_{1l}+\alpha_{2l})^2+v^2\max(\alpha_{2l}^2, \beta_l^{*2})](c_h-c_l), \quad \text{(IC}l\text{–r)}$$

$[s(\alpha_{1h}+\alpha_{2h})^2+v^2\beta_h^{*2}](c_h-c_l)$

$$\geq [s(\alpha_{1l}+\alpha_{2l})^2+v^2\max(\alpha_{2l}^2, \beta_l^{*2})](c_h-c_l). \quad \text{(IC}l\text{–a)}$$

We make the following observations about the optimal solution. First, $\alpha_{1h}^*=0$. If $\alpha_{1h}>0$, then decreasing α_{1h} and increasing α_{2h} by a sufficiently small and same amount would not change the objective value and the second constraint, but doing so relaxes the first constraint. Second, $\alpha_{2l}^*=0$. If $\alpha_{2l}>0$, then decreasing α_{2l} and increasing α_{1l} by a sufficiently small and same amount would not decrease the objective value but relax both constraints. This proves parts (i) and (ii) of Proposition 6. Based on these two observations, it is then straightforward to solve (**P3**) by considering two cases. Let $\alpha_1=c_h/(c_h+1)$ and $\alpha_2=c_l/(c_l+1+(\rho/(1-\rho))(c_h-c_l))$. Note that the solution $\alpha_{2h}=\alpha_1$, $\alpha_{1l}=\alpha_2$ maximizes the objective value of (**P3**).

Case 1. If the solution $\alpha_{2h}=\alpha_1$, $\alpha_{1l}=\alpha_2$ satisfies the constraint (ICl–r)—i.e., $(s+v^2)\alpha_1^2 \geq s\alpha_2^2+v^2\beta_l^{*2}$—then this solution is also the optimal solution to (**P3**), because it not only maximizes the objective value of and but also satisfies (ICl–a). In this case,

$$\Pi^{\theta*}=\frac{s(s+\lambda^2)}{2}+\rho s[\Gamma(sc_h, sc_h+s)+\Gamma(v^2c_h, v^2c_h+\lambda^2)]$$

$$+(1-\rho)s\left[\Gamma\left(sc_l, sc_l+s+\frac{\rho}{1-\rho}s(c_h-c_l)\right)\right.$$

$$\left.+\Gamma\left(v^2c_l, v^2c_l+\lambda^2+\frac{\rho}{1-\rho}v^2(c_h-c_l), \beta_l^*\right)\right]. \quad (19)$$

Case 2. Otherwise, if $(s+v^2)\alpha_1^2 < s\alpha_2^2+v^2\beta_l^{*2}$, then (IC$l$–r) must be binding. In this case,

$$\Pi^{\theta*}=\max_{\alpha_{2h},\alpha_{1l}}\left\{\frac{s(s+\lambda^2)}{2}\right.$$

$$+\rho s[\Gamma(sc_h, sc_h+s, \alpha_{2h})+\Gamma(v^2c_h, v^2c_h+\lambda^2)]$$

$$+(1-\rho)s\left[\Gamma\left(sc_l, sc_l+s+\frac{\rho}{1-\rho}s(c_h-c_l), \alpha_{1l}\right)\right.$$

$$\left.\left.+\Gamma\left(v^2c_l, v^2c_l+\lambda^2+\frac{\rho}{1-\rho}v^2(c_h-c_l), \beta_l^*\right)\right]\right\}$$

s.t. $(s+v^2)\alpha_{2h}^2(c_h-c_l)=(s\alpha_{1l}^2+v^2\beta_l^{*2})(c_h-c_l), \quad (20)$

which can be solved by a one-dimensional search over α_{2h}.

If $v<\lambda$, then $\alpha_1>\beta_h^* \geq \beta_l^*$. Thus, Case 1 holds and $\alpha_{2h}^*=\alpha_1>\beta_h^*$. If $v\geq\lambda$, then $\beta_h^* \geq \alpha_1$ and $\beta_h^* \geq \beta_l^*$. This, together with the fact that $\alpha_{2h}^* \leq \max(\alpha_1, \beta_l^*)$ (because in Case 1, $\alpha_{2h}^*=\alpha_1$, and in Case 2, $\alpha_{2h}^* < \beta_l^*$), implies that $\alpha_{2h}^* \leq \beta_h^*$. This proves part (iii).

The Optimal Contingent Royalty Contracts Without Revision

By going through the same solution procedure of (**P2**), we can simplify the marketer's contract design problem as follows:

$$\hat{\Pi}^{\theta*}=\max_{\hat{\alpha}_{1h}, \hat{\alpha}_{2h}, \hat{\alpha}_{1l}, \hat{\alpha}_{2l}}\left\{\frac{s(s+\lambda^2)}{2}+\rho s[\Gamma(sc_h, sc_h+s, \hat{\alpha}_{1h}+\hat{\alpha}_{2h})\right.$$

$$+\Gamma(v^2c_h, v^2c_h+\lambda^2, \hat{\alpha}_{2h})]$$

$$+(1-\rho)s\left[\Gamma\left(sc_l, sc_l+s+\frac{\rho}{1-\rho}s(c_h-c_l), \hat{\alpha}_{1l}+\hat{\alpha}_{2l}\right)\right.$$

$$\left.\left.+\Gamma\left(v^2c_l, v^2c_l+\lambda^2+\frac{\rho}{1-\rho}v^2(c_h-c_l), \hat{\alpha}_{2l}\right)\right]\right\},$$

which can be solved in two cases.

Case 1. If $v<\lambda$, then $\hat{\alpha}_{1h}^*=c_h/(c_h+1)-v^2c_h/(v^2c_h+\lambda^2)$ and $\hat{\alpha}_{2h}^*=v^2c_h/(v^2c_h+\lambda^2)$; $\hat{\alpha}_{1l}^*=c_l/(c_l+1+(\rho/(1-\rho))\cdot(c_h-c_l))-v^2c_l/(v^2c_l+\lambda^2+(\rho/(1-\rho))v^2(c_h-c_l))$ and $\hat{\alpha}_{2l}^*=v^2c_l/(v^2c_l+\lambda^2+(\rho/(1-\rho))v^2(c_h-c_l))$; and

$$\hat{\Pi}^{\theta*}=\frac{s(s+\lambda^2)}{2}+\rho s[\Gamma(sc_h, sc_h+s)+\Gamma(v^2c_h, v^2c_h+\lambda^2)]$$

$$+(1-\rho)s\left[\Gamma\left(sc_l, sc_l+s+\frac{\rho}{1-\rho}s(c_h-c_l)\right)\right.$$

$$\left.+\Gamma\left(v^2c_l, v^2c_l+\lambda^2+\frac{\rho}{1-\rho}v^2(c_h-c_l)\right)\right]. \quad (21)$$

Case 2. If $v\geq\lambda$, then $\hat{\alpha}_{1h}^*=0$ and $\hat{\alpha}_{2h}^*=(sc_h+v^2c_h)/(sc_h+s+v^2c_h+\lambda^2)$; $\hat{\alpha}_{1l}^*=0$ and $\hat{\alpha}_{2l}^*=(sc_l+v^2c_l)/(sc_l+s+v^2c_l+\lambda^2+(\rho/(1-\rho))(s+v^2)(c_h-c_l))$; and

$$\hat{\Pi}^{\theta*}=\frac{s(s+\lambda^2)}{2}+\rho s\Gamma(sc_h+v^2c_h, sc_h+s+v^2c_h+\lambda^2)$$

$$+(1-\rho)s\Gamma\left(sc_l+v^2c_l, sc_l+s+v^2c_l+\lambda^2\right.$$

$$\left.+\frac{\rho}{1-\rho}(s+v^2)(c_h-c_l)\right). \quad (22)$$

Proof of Proposition 7

(i) If $v<\lambda$, it follows from the above analysis that $\hat{\alpha}_1^*=c/(c+1)-v^2c/(v^2c+\lambda^2)>0$, $\hat{\alpha}_2^*=v^2c/(v^2c+\lambda^2)>0$, and $\hat{\Pi}^{\theta*}=s(s+\lambda^2)/2+s[\Gamma(sc, sc+s)+\Gamma(v^2c, v^2c+\lambda^2)]$. In this case, because $\alpha_1=\alpha_2=c/(c+1)$ and $\alpha_1>\beta^*=v^2c/(v^2c+\lambda^2)$, we have $(s+v^2)\alpha_1^2 \geq s\alpha_2^2+v^2\beta^{*2}$. Hence, it follows from (19) that $\Pi^{\theta*}=s(s+\lambda^2)/2+s[\Gamma(sc, sc+s)+\Gamma(v^2c, v^2c+\lambda^2)]$. Therefore, $\hat{\Pi}^{\theta*}=\Pi^{\theta*}$. (ii) If $v\geq\lambda$, then $\hat{\alpha}_1^*=0$, $\hat{\alpha}_2^*=(sc+v^2c)/(sc+s+v^2c+\lambda^2)>0$, and $\hat{\Pi}^{\theta*}=s(s+\lambda^2)/2+s\Gamma(sc+v^2c, sc+s+v^2c+\lambda^2)$. In this case, because $\alpha_1=\alpha_2=c/(c+1)$ and $\alpha_1 \leq \beta^*=v^2c/(v^2c+\lambda^2)$, we have $(s+v^2)\alpha_1^2 \leq s\alpha_2^2+v^2\beta^{*2}$. Hence, it follows from (20) that $\Pi^{\theta*}=s(s+\lambda^2)/2+s[\Gamma(sc_h, sc_h+s)+\Gamma(v^2c, v^2c+\lambda^2)]$. Thus, we have $d(\Pi^{\theta*}-\hat{\Pi}^{\theta*})/dv=2svc(\beta^*-\beta^{*2}/2-(\hat{\alpha}_2^*-\hat{\alpha}_2^{*2}/2))$. Because $\beta^* \leq 1$ and $\hat{\alpha}_2^* \leq 1$, the sign of $d(\Pi^*-\hat{\Pi}^*)/dv$ is the same as that of $\beta^*-\hat{\alpha}_2^*$, which is positive for $v>\lambda$. This, together with the fact that $\Pi^{\theta*}=\hat{\Pi}^{\theta*}$ when $v=\lambda$, completes the proof.

Proof of Proposition 8

(i) If $v=\lambda=1$, then $\alpha_1>\beta_l^*$ and hence $(s+v^2)\alpha_1^2 \geq s\alpha_2^2+v^2\beta_l^{*2}$. Therefore, by (19) and (22), $\Pi^{\theta*}-\hat{\Pi}^{\theta*}<0$. Further, fixing c_l and letting $\Delta=c_h-c_l$ vary, we have $d(\Pi^{\theta*}-\hat{\Pi}^{\theta*})/d\Delta=s\rho(\alpha_l^{*2}/2-\beta_l^{*2}/2)$, where $\alpha_l^*=c_l/(c_l+1+(\rho/(1-\rho))\Delta)<\beta_l^*$

for $\Delta > 0$. Hence, $d(\Pi^{\theta *} - \hat{\Pi}^{\theta *})/d\Delta < 0$ for $\Delta > 0$. (ii) Suppose $c_h = +\infty$. Then $\alpha_1 = 1$, $\alpha_2 = 0$, and thus $(s + v^2)\alpha_1^2 \geq s\alpha_2^2 + v^2\beta_l^{*2}$. Therefore, by (19) and $\beta_l^* > 0$, $\Pi^{\theta *} = -\infty$. On the other hand, $\hat{\Pi}^{\theta *} > 0$. Thus, as c_h is sufficiently large, $\Pi^{\theta *} < \hat{\Pi}^{\theta *}$. Therefore, there exists a threshold $\delta \in (0, \infty)$ such that if $c_h - c_l > \delta$, $\Pi^{\theta *} - \hat{\Pi}^{\theta *} < 0$. (iii) If $v \leq \lambda$, then (21) holds. Further, because $\alpha_1 \geq \beta_l^*$, $(s + v^2)\alpha_1^2 \geq s\alpha_2^2 + v^2\beta_l^{*2}$, implying that (19) holds. Thus, $\hat{\Pi}^{\theta *} - \Pi^{\theta *} > 0$.

Proof of Proposition 9

(i) The result follows directly from part (iii) of Proposition 8 and the fact that the marketer is no worse off under contingent contracts than under noncontingent contracts; i.e., $\hat{\Pi}^{\theta *} \geq \hat{\Pi}^*$ and $\Pi^{\theta *} \geq \Pi^*$. (ii) If $v > \lambda$, then (22) holds, implying that $\hat{\Pi}^{\theta *} = \hat{\Pi}^*$. This, together with the fact that $\Pi^{\theta *} \geq \Pi^*$, suggests that $\Pi^{\theta *} - \hat{\Pi}^{\theta *} \geq \Pi^* - \hat{\Pi}^*$.

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