Patent Protection and R&D Subsidy Under Asymmetric Information*

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Abstract

We examine a license contract in vertically separated market in which an upstream firm develops new technology that can save a downstream firm's running costs. We show that perfect patent protection is optimal under symmetric information, whereas it is not if the licensee cannot identify the technology's quality and the licensor's R&D cost efficiency. Furthermore, it is shown that social welfare under asymmetric information is higher than that under symmetric information for most patent protection level, yet the latter dominates the former in the presence of optimal policy for each regime. R&D subsidy is found to be suboptimal under symmetric information, whereas it can be optimal in the presence of information asymmetry. With these features, we derive a combination of patent protection and R&D subsidy that yields the first-best results in multiple industries at the same time. In spite of the suboptimality, R&D subsidy can stimulate the innovation of more efficient firms under symmetric information at the expenses of losses in social welfare, while that of less efficient ones is rather delayed. Under asymmetric information, however, it neither stimulates nor stifles innovation unless too much is granted. It is shown that information asymmetry induces underinvestment of less efficient firms and overinvestment of more efficient ones, especially in the presence of R&D subsidy.

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1 Introduction

A licensing contract bridges the gap between innovators and manufacturers by arranging how much and from when to pay royalties to make use of new technology. The contract, however, guarantees the licensee the right to produce, *not the profitability* (e.g., Shepard (1987)). In most cases, there exists information asymmetry regarding the technology's quality between the licensor and the licensee, and this can lead to inefficient contract that harms social welfare. The government's policies on patent rights and R&D subsidy directly affect the terms and the timing of licensing contract, and are expected to mitigate the problem effectively.

In this paper, we investigate a license contract in vertically separated market under asymmetric information. Namely, the upstream firm develops new technology that can save running costs of the downstream firm, but the downstream firm cannot identify the upstream firm's true type in terms of the quality of the cost-saving technology and R&D cost efficiency. We study how much protection should be given to patent holders under different types of information structure. Furthermore, we examine the efficiency of R&D subsidy in the presence of vertical separation and derive the optimal policy as a combination of patent protection and R&D subsidy that can maximize social welfare in multiple industries at the same time. The model is based on real options framework, which allows us to analyze the effects of information asymmetry and R&D subsidy on innovation from dynamics perspective.

First of all, we show that perfect patent protection is optimal under symmetric information, whereas it is not in the presence of information asymmetry. Since the downstream firm gets a free ride on the innovation led by the upstream firm, the government should apportion the whole surplus to the innovator by providing perfect protection on patent rights. If the downstream firm is uninformed about the technology's quality, however, the dominant innovator with more efficient R&D process has to make the investment earlier than it would have made under symmetric information to separate itself from the dominated one and receive a fair amount of royalties. That is, earlier innovation becomes a signal of being a dominant firm, from which the downstream firm always benefits. Thus, patent protection needs to be adjusted taking the distortion in investment timing by information asymmetry into account.

Furthermore, it is shown that social welfare under asymmetric information is higher than that under symmetric information for most patent protection level. This counterintuitive result comes from the fact that the downstream firm's benefits from earlier innovation can dominate the upstream firm's losses from the distortion in investment timing. In other words, information asymmetry can rather raise the total amount of wealth in society for a given patent policy. This result is in contrast to Anton and Yao (2003) which investigated the process of innovation with a signaling via disclosure and showed that information asymmetry yields excessive disclosure which always harms social welfare. With the optimal patent policy for each regime, however, social welfare under symmetric information dominates that under asymmetric information.

We also found that R&D subsidy is always suboptimal under symmetric information in that social welfare strictly decreases in the amount of the subsidy. That is, innovation is not stimulated enough to offset the government's expenditure on the subsidy. This argument, however, does not hold when there is information asymmetry in the market; we can yield the first-best result even in the presence of R&D subsidy unless too much subsidies are given. This is because it has a proper function of mitigating the distortion in the innovator's investment timing by disincentivizing the dominated firm to mimic the dominant one. Namely, relative differences in R&D costs of different types of innovators increase in the amount of subsidy, which makes the dominated firm harder to invest earlier to mimic the the dominant one.

With these features of R&D subsidy, we derive the optimal policy as a combination of patent protection and R&D subsidy that yields the first-best results in multiple industries at the same time. It is obvious that different industries need different level of patent protection but it is infeasible to set patent policies for each industry. Yet, it is possible to grant different amount of R&D subsidy to the firms in different industries. We show that patent protection should be set as the lowest level among the optimal ones for each industry and R&D subsidy is to be granted to the firms in the industry with suboptimal patent protection.

Even though R&D subsidy does not improve the level of social welfare under both information structure, it is worth noting its effects on the timing of innovation. Under symmetric information, more efficient firms invest earlier with R&D grants at the expense of losses in social welfare, while less efficient ones delay the investment in spite of the grants due to the indirect effects from the optimal patent policy. This result is in line with Lach (2002) which provides empirical evidences of both positive and negative effects of R&D subsidies on the firms' R&D expenditure. Under asymmetric information, however, the subsidy neither stimulates nor stifles the innovation unless too much is given, which is consistent with empirical evidences from Wallsten (2000) and Klette and Møen (2012).

In terms of the effects of information asymmetry on the timing of innovation, we show that less efficient firms always underinvest under asymmetric information, whereas more efficient ones can overinvest, provided the optimal policy for each information structure. These effects become even clearer in the presence of R&D subsidy in that more efficient firms always overinvest in R&D projects under asymmetric information. The novelty of these results can be found from the fact that underinvestment and overinvestment in R&D projects have usually been attributed to constraints of external financing and competition in the market, respectively, in traditional literature, while we found them from information asymmetry.

A vast literature is dedicated to a signaling game in technology market, and many of them have regarded the terms of license contract as a signal of private information. Gallini and Wright (1990) assumed that a licensor has private information on economic value of new technology and signals it by the form of royalty contract (e.g., linear or nonlinear, exclusive or nonexclusive). Beggs (1992) supposed that a licensee knows the value of patents better than a licensor and showed that the royalty payment is dominant over fixed fees.[1] Martimort, Poudou, and Sand-Zantman (2010) presumed bilateral asymmetric information in terms of innovators' quality and developers' effort level, addressing that best innovators signal their type by taking more royalties even if it reduces the developers' incentives to license.

[1]Schmitz (2002) also assumed that a licensee, not a licensor, has private information on the profitability of new technology.

There has been another stream of research on inventors' signaling which focuses on the disclosure of information. Bhattacharya and Ritter (1983) supposed that innovators disclose their private information for the sake of external financing. Anton and Yao (1994) and Anton and Yao (2002) examined a vertically separated market with downstream duopoly, addressing that an upstream firm has an incentive to reveal its private information prior to the contract, even in the absence of property rights.[2] Anton and Yao (2003) and Anton and Yao (2004) demonstrated that the leader has an incentive to disclose its private information in spite of the follower's imitation.[3] Gick (2008) focused on small firms' signaling scenario in which two inventors compete in the upstream market while a downstream firm has an option not to cooperate with them, and showed that the inventor chooses to disclose via patent filing even in the presence of disclosure costs.

None of these papers, however, investigated the innovator's R&D investment decision. Namely, they assumed that inventors discover new technology without any costs. In contrast, we endogenize the innovator's decision on the timing of R&D investment and regard it as a signal of technology's quality to the licensee under asymmetric information. This novel approach on R&D investment and the government's policies sheds light on the dynamics perspective of the licensing game that has received little attention from the existing literature. Recent years have seen an increasing discussion about a signaling game via investment timing. Morellec and Schürhoff (2011) adopted this approach to examine a firm's decision on investment and financing, while Bustamante (2012) investigated IPO market with a signaling of investment quality. Grenadier and Malenko (2011) formulated this framework in a general setup and provided a number of examples of its applications in corporate finance.

Meanwhile, much has been discussed about optimal patent policy and most of them have examined the problem in the context of deadweight loss,[4] sequetial innovation,[5] and competition by imitation.[6] Yet, relatively little attention has been paid to the patent policy in the presence of vertical separation. Lerner and Tirole (2004) assumed downstream users of which surplus strictly increases in the number of patents licensed, and demonstrated the necessity of patent pools in technology market. Farrell and Shapiro (2008) supposed oligopoly in the downstream market and a licensing with two-part tariff, addressing that weak patents of which validity can be lost by litigation is dominant over ironclad patents that incur significant examination costs. Jeon and Nishihara (2017) investigated a vertically separated market and derived optimal patent policy as a mix of probabilistic validity and damages upon infringement. These papers, however, did not discuss how strong patent should be in the presence of asymmetric information under which a license contract in the real world is usually made. Our model examines this issue and extends the discussion by incorporating R&D subsidy as another axis of the government's

[2]Anton and Yao (1994) examined a contract between an inventor and two manufacturing firms, while Anton and Yao (2002) studied a contract between a seller who has ideas for innovation and two inventors.

[3]Anton and Yao (2003) focused on product-innovation under which the follower cannot produce without the leader's disclosure of technology, while Anton and Yao (2004) was dedicated to process-innovation under which the follower can use the existing technology as well.

[4]See Gilbert and Shapiro (1990), Klemperer (1990), and Denicolò (1996).

[5]See Scotchmer (1991), Green and Scotchmer (1995), Chang (1995), and Scotchmer (1996).

[6]See Choi (1998), Aoki and Hu (1999), Wright (1999), Anton and Yao (2006), and Choi (2009).

policies.

Despite the plethora of research on R&D subsidy, no consensus has been reached regarding its effectiveness in both theoretical and empirical models. Spence (1984) argued that positive subsidy is optimal in the presence of spillover, and Hinloopen (1997) supported this claim by showing that R&D subsidy is more effective than R&D cooperation. Yet, Lahiri and Ono (1999) refuted this argument based on more general demand function, addressing that a firm with cost advantage should be subsidized while a firm without it should be taxed. Gick (2008) studied a signaling game of innovation via disclosure and found that the subsidization of patent filing costs is socially wasteful in that it induces excessive disclosure. Empirical evidences present a mixed results as well. Even though many studies have shown that the subsidy does stimulate R&D activities,[7] there also exist researches that show the evidence of no stimulation (e.g., Wallsten (2000) and Klette and Møen (2012)[8]) and the crowding out effects (e.g., Busom (2000), Klette, Møen, and Griliches (2000), David, Hall, and Toole (2000), and Lach (2002)). Our model clarifies the interaction between R&D subsidy and patent protection under different types of information structure, and reveals both positive and negative effects of R&D subsidy on the timing of innovation and social welfare.

The remainder of this paper is organized as follows. We illustrate the setup of the model in Section 2.1 and derive the firm's investment decision under symmetric information as a benchmark in Section 2.2. We introduce asymmetric information in Section 2.3 and examine how it changes the investment decision and the optimal patent policy. In Section 3, we incorpate R&D subsidy into the model and investigate its effects on the timing of innovation and social welfare under symmetric and asymmetric information in Sections 3.1 and 3.2, respectively. Section 4 presents the results of comparative statics for the parameters given in Section 4.1; the discussion on the degree of asymmetry in technology's quality and R&D cost efficiency is given in Sections 4.2 and 4.3, respectively, while that on the proportion of innovators with different types is given in Section 4.4. Section 5 provides a brief summary of the main results of this research.

2 The model and solutions

2.1 Setup

Suppose there is a downstream firm that makes a product of which demand shock is given by a one-dimensional geometric Brownian motion as follows:

$$\mathrm{d}X_t = \mu X_t \mathrm{d}t + \sigma X_t \mathrm{d}W_t \tag{1}$$

where μ and σ are positive constants and $(W_t)_{t\geq 0}$ is a standard Brownian motion on a filtered probability space $(\Omega, \mathcal{F}, \mathbb{F} := (\mathcal{F}_t)_{t\geq 0}, \mathbb{P})$ satisfying the usual conditions. A risk-free rate is given by a constant $r > \mu$ to ensure the finiteness of value functions. By manufacturing the product,

[7] See Czarnitzki and Toole (2007), González and Pazó (2008), and Hussinger (2008).

[8] They found that the subsidy neither stimulates nor stifles firms' R&D investment.

the downstream firm makes revenue flows πX_t, and the production costs c per unit. Thus, its current value can be written as follows:

$$\mathbb{E}\Big[\int_t^\infty e^{-r(s-t)}(\pi - c)X_s \mathrm{d}s\Big| X_t = x\Big] = \frac{(\pi - c)x}{r - \mu} \tag{2}$$

Meanwhile, there is an upstream firm which can carry out R&D investment at lump-sum costs δ and develop new technology that can save the downstream firm's running costs by $\gamma \in (0, 1)$. Since the upstream firm does not have its own production facilities, it can only raise revenue by licensing the cost-saving technology to the downstream firm. That is, the upstream and the downstream firms share the surplus from the innovation by a licensing contract: the former and the latter take a fraction λ and $1-\lambda$ of the surplus from the cost-saving technology, respectively, where $\lambda \in [0, 1]$ stands for the degree of patent protection.

Furthermore, we assume there are two different types of the upstream firm; type g and type b. The former dominates the latter in terms of the quality of technology and the R&D efficiency; $\gamma_g > \gamma_b$ and $\delta_g < \delta_b$. Namely, type g can develop more innovative technology at lower costs.[9] The probability that the upstream firm's type is g and b is given by p and $1 - p$, respectively, where $p \in (0, 1)$. In other words, p denotes the proportion of more efficient firms in the upstream market.

2.2 Benchmark model: symmetric information

Before getting into the main model in which there exists asymmetric information regarding the upstream firm's type, we examine a licensing contract of new technology under symmetric information first as a benchmark model.

Suppose the downstream firm can identify the upstream firm's true type. The license fee of newly developed technology is determined based on the quality of the technology and the patent protection and is chosen as $\lambda\gamma_i c$ per unit for $i \in \{g, b\}$. Given these royalties which can be raised after the innovation, we can examine the upstream firm's decision on the R&D investment timing. It is well-known from real options theory that a firm's option value $v(x)$ satisfies the following ordinary differential equation:

$$rv = \mu x \frac{\mathrm{d}v}{\mathrm{d}x} + \frac{1}{2}\sigma^2 x^2 \frac{\mathrm{d}^2 v}{\mathrm{d}x^2} \tag{3}$$

of which solution takes the form of

$$v(x) = Ax^\alpha + Bx^\beta \tag{4}$$

where

$$\alpha = \frac{1}{2} - \frac{\mu}{\sigma^2} + \sqrt{\Big(\frac{1}{2} - \frac{\mu}{\sigma^2}\Big)^2 + \frac{2r}{\sigma^2}} > 1, \qquad \beta = \frac{1}{2} - \frac{\mu}{\sigma^2} - \sqrt{\Big(\frac{1}{2} - \frac{\mu}{\sigma^2}\Big)^2 + \frac{2r}{\sigma^2}} < 0 \tag{5}$$

[9] A number of papers have investigated the effects of incomplete information regarding the profitability (e.g., Gallini and Wright (1990), Beggs (1992), Schmitz (2002)) and the cost structure (e.g., Anton and Yao (2003), Bessen (2004), Gick (2008), Martimort, Poudou, and Sand-Zantman (2010)). In this paper, we follow the fashion of Grossman and Horn (1988) and Chen (1991) which presumed that the marginal costs of producing high quality is lower for firms with higher efficiency.

Note that $B = 0$ holds due to the boundary condition of $v(0) = 0$. By the standard argument from real options literature, we can derive the value function of the upstream firm of type $i \in \{g, b\}$ under symmetric information as follows:

$$U_i^s(x) = \left[\frac{\lambda\gamma_i c X_i}{r-\mu} - \delta_i\right]\left(\frac{x}{X_i}\right)^\alpha \tag{6}$$

where

$$X_i = \frac{\alpha(r-\mu)\delta_i}{(\alpha-1)\lambda\gamma_i c} \tag{7}$$

Note that $X_g < X_b$ holds because of $\gamma_g > \gamma_b$ and $\delta_g < \delta_b$. That is, the dominant firm with more innovative technology and more efficiency in R&D process invests earlier than the dominated one. It is also natural that $\partial X_i/\partial\lambda < 0$ holds; the stronger patent protection is, the earlier the innovation is made.

The downstream firm will adopt the cost-saving technology as soon as it becomes available, and thus, the value of the downstream firm making the license contract with the upstream firm of type $i \in \{g, b\}$ under symmetric information is derived as follows:

$$D_i^s(x) = \frac{(\pi - c)x}{r-\mu} + \frac{(1-\lambda)\gamma_i c X_i}{r-\mu}\left(\frac{x}{X_i}\right)^\alpha \tag{8}$$

Note that $\partial D_i^s(x)/\partial X_i < 0$ holds; the earlier the innovation is made, the more the downstream firm benefits from it. This is because the downstream firm enjoys the surplus from the cost-saving technology without any contribution to its development. In other words, the downstream firm gets a free ride on the innovation solely led by the upstream firm. This argument becomes even clearer when we evaluate social welfare as follows:

$$W^s(x) = pW_g^s(x) + (1-p)W_b^s(x) \tag{9}$$

where

$$W_i^s(x) = U_i^s(x) + D_i^s(x) \tag{10}$$

$$= \frac{(\pi - c)x}{r-\mu} + \left[\frac{\gamma_i c X_i}{r-\mu} - \delta_i\right]\left(\frac{x}{X_i}\right)^\alpha \quad \forall i \in \{g, b\} \tag{11}$$

Insert Figure 1 here.

Figure 1 presents the results from comparative statics of regarding the patent protection λ based on parameters given in Section 4.1. We can clearly see from Panel (a) that the upstream firm's value monotonically increases in λ, which is a natural result. The downstream firm's value, however, is not monotone with respect to λ (Panel (b)). As mentioned before, it monotonically decreases in X_i for $i \in \{g, b\}$; the earlier the innovation is made, the more the downstream firm benefits from it. The increase of λ advances the development of new technology (Panels (c) and (d)), which raises the downstream firm's value while λ is sufficiently low. After λ exceeds a certain level, however, the burden of higher royalties dominates the gains from earlier innovation, and the downstream firm's value starts to decrease in λ.

Meanwhile, we can see from Panel (e) that social welfare as the sum of both firms' value monotonically increases in λ. This implies that perfect protection on patents is optimal under symmetric information, and the reason is as follows. We can see from (11) that the level of social welfare coincides with the value of a hypothetical firm into which the upstream and the downstream firms are vertically integrated. Thus, the policymaker's decision on the patent protection λ to maximize social welfare is equivalent to the hypothetical firm's decision to maximize its value. In this regard, we can easily see that $\lambda_s^* = 1$ is the optimal policy since it yields the optimal investment timing of the hypothetical firm with profits flow $\gamma_i c X_t$ and investment costs δ_i for $i \in \{g, b\}$. This result implies that to maximize social welfare under symmetric information, the whole surplus from the innovation should be apportioned to the one to which the innovation is attributed. In other words, we can have the same results of vertical integration by compensating the firms according to their contribution to the innovation. This is in line with the desirable direction of patent reform suggested by Shapiro (2008).

It is worth noting that social welfare is maximized when innovation is made at its earliest time. Namely, we can see from Panels (c), (d), and (e) that W^s is the highest when X_g and X_b are the lowest. This result can be read from the perspective of consumer surplus in that the earlier the invention is made, the more consumers benefit from it. As will be shown shortly, however, this monotonicity between the investment timing and the level of social welfare does not hold when there exists information asymmetry in the market.

2.3 Main model: asymmetric information

Now we shall proceed to the main model in which there exists asymmetric information regarding the upstream firm's type. Suppose the downstream firm cannot identify the quality of the technology before it actually uses it[10] and a licensing contract is irreversible in that the terms cannot be changed once they seal the deal.

Given higher royalties for type g firm, type b has an incentive to mimic type g's investment behavior. That is, type b can choose to invest earlier than it would have done under symmetric information to pretend to be type g so that it gets higher royalties from the licensee. In spite of the incomplete information, the downstream firm can observe the counterparty's investment behavior. Thus, the upstream firm's investment timing plays a role of a signal of its type.[11] If the upstream firm of type i invests at the threshold X and the quality of its technology is perceived as γ, the firm value is evaluated as follows:

$$U_i^a(x; X, \gamma) = \left[\frac{\lambda \gamma c X}{r - \mu} - \delta_i\right]\left(\frac{x}{X}\right)^{\alpha} \quad \forall i \in \{g, b\} \tag{12}$$

[10] This assumption can be construed in the context of "experience goods" discussed in Grossman and Horn (1988) and Chen (1991). They analyzed informational barriers to enter the market and supposed that consumers do not know the value of the goods until they use it.

[11] Many studies have investigated a signaling game under asymmetric information in technology market. Some of them discussed a signaling via disclosure (e.g., Bhattacharya and Ritter (1983), Anton and Yao (1994), Anton and Yao (2003), Anton and Yao (2004), Gick (2008)) while others studied a signaling via the terms of license contract (e.g., Gallini and Wright (1990), Beggs (1992), Martimort, Poudou, and Sand-Zantman (2010)). In this paper, we limit ourselves to the royalties contract and exclude the possibility of disclosure, focusing on the dynamics perspective of license contract.

and the following holds regarding the sensitivity of the valuation:

$$\frac{\partial}{\partial X}U_i^a(x;X,\gamma) = \Big[\frac{(1-\alpha)\lambda\gamma c}{r-\mu} + \frac{\alpha\delta_i}{X}\Big]\Big(\frac{x}{X}\Big)^\alpha \tag{13}$$

$$\frac{\partial}{\partial \gamma}U_i^a(x;X,\gamma) = \frac{\lambda c X}{r-\mu}\Big(\frac{x}{X}\Big)^\alpha \tag{14}$$

Meanwhile, the following equation holds along any iso-value curve:

$$\frac{\partial}{\partial X}U_i^a(x;X,\gamma) + \frac{\partial}{\partial \gamma}U_i^a(x;X,\gamma)\frac{\partial\gamma}{\partial X} = 0 \tag{15}$$

Thus, the elasticity of substitution between the perceived quality of the technology γ and the investment timing X can be derived as follows:

$$\frac{\partial\gamma}{\partial X}\frac{X}{\gamma} = -\frac{\frac{\partial}{\partial X}U_i^a(x;X,\gamma)}{\frac{\partial}{\partial \gamma}U_i^a(x;X,\gamma)}\frac{X}{\gamma} \tag{16}$$

$$= (\alpha-1) - \frac{\alpha\delta_i(r-\mu)}{\lambda\gamma c X} \tag{17}$$

We can see that the single crossing (or Spencer-Mirrless) condition holds in that (17) negatively depends on δ_i and $\delta_g < \delta_b$.[12] Namely, type g firm finds it less costly to distort its investment timing than type b. Thus, type g can choose to carry out R&D investment earlier than it would have done under symmetric information so that type b sticks to its investment trigger X_b and the downstream firm can tell type g from type b.

It is possible to discuss regarding a pooling equilibrium in which the upstream firms with both types invest at the same trigger and the license fee is chosen based on the expectation of the technology's quality (i.e., $p\gamma_g+(1-p)\gamma_b$). Yet, it is well-known that the pooling equilibrium does not satisfy the Intuitive Criterion from Cho and Kreps (1987) and suffers from the multiplicity of equilibrium. Thus, we limit ourselves to the (least-cost) separating equilibrium in the present model.[13]

Type b firm has an incentive to mimic type g by investing at the trigger X when the following condition holds:

$$\Big[\frac{\lambda\gamma_g c X}{r-\mu} - \delta_b\Big]\Big(\frac{x}{X}\Big)^\alpha \geq \Big[\frac{\lambda\gamma_b c X_b}{r-\mu} - \delta_b\Big]\Big(\frac{x}{X_b}\Big)^\alpha = U_b^s(x) \tag{18}$$

In other words, type b is willing to bear the costs of distortion in the investment timing as long as the gains from the increased royalties are high enough to satisfy (18). Thus, we can derive the trigger X^* under which type b gives up on mimicking type g from the binding condition of (18).

Similarly, type g firm's incentive compatibility condition to separate itself from type b by deviating from the first-best investment trigger X_g is as follows:

$$\Big[\frac{\lambda\gamma_g c X}{r-\mu} - \delta_g\Big]\Big(\frac{x}{X}\Big)^\alpha \geq \Big[\frac{\lambda\gamma_b c X_b}{r-\mu} - \delta_g\Big]\Big(\frac{x}{X_b}\Big)^\alpha \tag{19}$$

[12] See Chapter 7 of Fudenberg and Tirole (1991) for a fuller discussion on a single crossing condition in a signaling game.

[13] Martimort, Poudou, and Sand-Zantman (2010) and Grenadier and Malenko (2011) also documented that the separating equilibrium is the unique equilibrium under the assumption that out-of equilibrium beliefs must satisfy the restriction specified by the D1 refinement.

The binding condition of (19) yields $X^*_{\max}$ over which type g gives up on separating itself from type b due to the high costs of distortion in the investment timing. Thus, the separating equilibrium exists only if $X^* \leq X^*_{\max}$ holds.

Following these arguments, we can derive the value functions of the upstream firm of each type under asymmetric information as follows:

$$U^a_g(x) = \begin{cases} \left[\frac{\lambda\gamma_g cX^*}{r-\mu} - \delta_g\right]\left(\frac{x}{X^*}\right)^\alpha & \text{if } X^* < X_g \\ U^s_g(x) & \text{if } X^* \geq X_g \end{cases} \tag{20}$$

$$U^a_b(x) = U^s_b(x) \tag{21}$$

Note that type g firm invests at the trigger X_g when $X^* \geq X_g$; if type g can separate itself from type b at its first-best investment timing, there is no reason to deviate from it.

Similarly, the value of the downstream firm making the license contract with each type of upstream firm under asymmetric information is derived as follows:

$$D^a_g(x) = \begin{cases} \frac{(\pi-c)x}{r-\mu} + \left[\frac{(1-\lambda)\gamma_g cX^*}{r-\mu}\right]\left(\frac{x}{X^*}\right)^\alpha & \text{if } X^* < X_g, \\ D^s_g(x) & \text{if } X^* \geq X_g \end{cases} \tag{22}$$

$$D^a_b(x) = D^s_b(x) \tag{23}$$

Thus, the level of social welfare under asymmetric information can be evaluated as follows:

$$W^a(x) = pW^a_g(x) + (1-p)W^a_b(x) \tag{24}$$

where

$$W^a_g(x) = U^a_g(x) + D^a_g(x) \tag{25}$$

$$= \begin{cases} \frac{(\pi-c)x}{r-\mu} + \left[\frac{\gamma_g cX^*}{r-\mu} - \delta_g\right]\left(\frac{x}{X^*}\right)^\alpha & \text{if } X^* < X_g \\ W^s_g(x) & \text{if } X^* \geq X_g \end{cases} \tag{26}$$

$$W^a_b(x) = W^s_b(x) \tag{27}$$

It is straightforward that $U^a_g(x) \leq U^s_g(x)$ holds because the upstream firm deviates from its first-best investment when $X^* < X_g$. In contrast, $D^a_g(x) \geq D^s_g(x)$ holds because the downstream firm value decreases in the investment trigger, which is chosen as $\min(X^*, X_g)(\leq X_g)$ under asymmetric information. In other words, the upstream firm, the inventor of new technology, suffers losses from information asymmetry, whereas the downstream firm, the free rider of innovation, benefits from it. We can clearly see these results from Panels (a) and (b) of Figure 1.

It is of special interest if social welfare monotonically increases in the level of patent protection under asymmetric information as well. As shown in Panel (e) of Figure 1, however, the monotonicity does not hold when the downstream firm is not informed about the counterparty's type. That is, the optimal patent policy that maximizes social welfare under asymmetric information denoted by λ^*_a is lower than 1. This result implies that perfect protection on patents always harms social welfare under asymmetric information, which is in a sharp contrast with the case of symmetric information. This is because the benefits from earlier innovation are dominated by the costs of distortion in the innovator's investment timing when patent protection is too strong. In other words, free-riding on the innovation can rather improve social welfare in the presence of asymmetric information. This can also be read from the context of consumer surplus. Panels (c), (d), and (e) show that the monotonicity between the timing of innovation and social welfare does not hold under asymmetric information as well. Thus, consumers cannot enjoy new technologies at their earliest time in the presence of asymmetric information.

Furthermore, we can see from Panel (e) that social welfare under asymmetric information is higher than that under symmetric information for most patent protection level. In other words, the distortion in R&D investment decision induced by information asymmetry can rather improve social welfare. This counterintuitive result comes from the fact that the downstream firm's value decreases in the investment trigger, of which value is lower under asymmetric information (i.e., $\min(X^*, X_g) \leq X_g$). In the presence of the optimal patent protection, however, social welfare under symmetric information dominates that under asymmetric information (i.e., $W^s(x; \lambda_s^*) \geq W^a(x; \lambda_a^*)$). This is because type g firm makes an inefficient investment decision under asymmetric information as long as $X^* < X_g$ holds for λ_a^*, whereas there is no dissipation of surplus under symmetric information with $\lambda_s^* = 1$.

Given the fact that type g invests earlier (i.e., $\min(X^*, X_g) \leq X_g$) while type b's investment decision remains the same as X_b under asymmetric information, one might think that information asymmetry only induces overinvestment of more efficient firms. Yet, we need to see how it changes the investment timing in the presence of optimal patent protection for each regime. Recall that $\lambda_s^* = 1$ and $\lambda_a^* < 1$ hold and that X_b monotonically decreases in λ (Panel (d) in Figure 1). Thus, $X_b(\lambda_a^*) > X_b(\lambda_s^*)$ always holds, which implies that given the optimal patent policy for each regime, less efficient innovators delay the R&D investment under asymmetric information. Note that the underinvestment in R&D projects occurs even without the constraints of external financing which has been attributed to the underinvestment in traditional literature on innovation (e.g., Lerner (1999), Hall (2002)).

The effects of information asymmetry on more efficient inventors' investment decision are less clear. We cannot affirm the direction of its effects because both X_g and X^* decrease in λ (Panel (c) in Figure 1) and $\lambda_a^* < \lambda_s^*(= 1)$ holds. Type g firm overinvests in R&D projects because of asymmetric information if $X^*(\lambda_a^*) < X_g(\lambda_s^*)(< X_g(\lambda_a^*))$ and underinvests if $X_g(\lambda_s^*) < \min(X^*(\lambda_a^*), X_g(\lambda_a^*))$; namely, it depends on how much information asymmetry changes the optimal patent policy. In the benchmark case in Figure 1, we observe the overinvestment of R&D projects by more efficient firms (Panel (c)). In traditional literatures, excessive R&D investment has been attributed to strategic substitution (e.g., Brander and Spencer (1983)[14]) or preemptive incentives (e.g., Miltersen and Schwartz (2004), Hsu and Lambrecht (2007), Leung and Kwok (2011)). Yet, we have shown the possibility of overinvestment in R&D projects even in the absence of the competition in the market. Anton and Yao (2003) investigated a signaling game via disclosure of information and also found that information symmetry yields excessive

[14]Brander and Spencer (1983) addressed that a firm's strategic behavior induces more R&D, but Leahy and Neary (1997) showed that it rather reduces R&D in the presence of spillover effects.

disclosure. The difference between their work and ours lies in the fact that excessive disclosure is always socially wasteful in their model, whereas it can be beneficial to the downstream firms and eventually improve social welfare in our model.

3 Extension of the model: R&D subsidy

The government might consider granting R&D subsidy to stimulate innovation at the expense of government expenditure, and we need to see if it really does and leads to the improvement of social welfare. As in Section 2, we examine the impact of R&D subsidy under symmetric information first and proceed to the analysis with information asymmetry later.

3.1 Symmetric information

In the presence of subsidy $\eta \in (0, \delta_g)$, the R&D investment costs reduce to $\hat{\delta}_i = \delta_i - \eta$ for $i \in \{g, b\}$, and the value of upstream and downstream firms for $i \in \{g, b\}$ can be evaluated in the same way as follows:

$$\hat{U}_i^s(x) = \Big[\frac{\lambda\gamma_i c\hat{X}_i}{r-\mu} - \hat{\delta}_i\Big]\Big(\frac{x}{\hat{X}_i}\Big)^\alpha \tag{28}$$

$$\hat{D}_i^s(x) = \frac{(\pi - c)x}{r-\mu} + \Big[\frac{(1-\lambda)\gamma_i c\hat{X}_i}{r-\mu}\Big]\Big(\frac{x}{\hat{X}_i}\Big)^\alpha \tag{29}$$

where

$$\hat{X}_i = \frac{\alpha(r-\mu)\hat{\delta}_i}{(\alpha-1)\lambda\gamma_i c} \tag{30}$$

The government's expenditure on the subsidy to the innovator of type $i \in \{g, b\}$ is

$$\hat{S}_i^s(x) = \eta\Big(\frac{x}{\hat{X}_i}\Big)^\alpha \tag{31}$$

and thus, social welfare in the presence of R&D subsidy under symmetric information can be evaluated as follows:

$$\hat{W}^s(x) = p\hat{W}_g^s(x) + (1-p)\hat{W}_b^s(x) \tag{32}$$

where

$$\hat{W}_i^s(x) = \hat{U}_i^s(x) + \hat{D}_i^s(x) - \hat{S}_i^s(x) \tag{33}$$

$$= \frac{(\pi - c)x}{r-\mu} + \Big[\frac{\gamma_i c\hat{X}_i}{r-\mu} - \delta_i\Big]\Big(\frac{x}{\hat{X}_i}\Big)^\alpha \quad \forall i \in \{g, b\} \tag{34}$$

Insert Figure 2 here.

Figure 2 presents the results from comparative statics with respect to η based on parameters in Section 4.1, and Panel (a) describes the level of $\hat{\lambda}_s^*(\eta)$, the optimal patent protection in the presence of R&D subsidy η. First of all, we can see that it strictly decreases in η and $\hat{\lambda}_s^*(\eta) < 1$ holds in contrast to $\lambda_s^* = 1$ for the case without R&D subsidy. In other words, given R&D subsidy granted by the government, perfect patent protection always harms social welfare even in the absence of information asymmetry. This is because both patent protection and R&D subsidy support the upstream firms' incentive to invest and the policymaker needs to keep the balance between these two instruments without overcompensating the innovators.

Meanwhile, we can clearly see from Panel (b) that social welfare decreases in η and $W^s(x;\lambda_s^*) > \hat{W}^s(x;\hat{\lambda}_s^*)$ always holds. That is, it is not possible to yield the first-best result with R&D subsidy under symmetric information (i.e., $\eta_s^* = 0$ where η_s^* denotes the maximum amount of R&D subsidy that can yield the first-best result under symmetric information), and the reason is as follows. From the viewpoint of a hypothetical firm whose objective is to maximize (34), the investment timing decision $\hat{X}_i$ is made based on the reduced costs $\hat{\delta}_i$ whereas the actual costs are δ_i for $i \in \{g, b\}$. The inefficient investment decision from this disparity can be mitigated by the patent policy λ. Namely, we can match $\hat{X}_i$ in (30) to $X_i(\lambda_s^*)$ in (7) for $i \in \{g, b\}$ by setting $\lambda = 1 - \eta/\delta_i$. As one can notice immediately, however, this value depends on the type of the innovator, and the optimal patent protection is chosen as $\hat{\lambda}_s^*(\eta) \in (1 - \eta/\delta_g, 1 - \eta/\delta_b)$ (Panel (a)). That is, a single level of patent protection cannot eliminate the inefficiency stemmed from R&D subsidy completely, and therefore, $W^s(x;\lambda_s^*) > \hat{W}^s(x;\hat{\lambda}_s^*)$ always holds.

Furthermore, Panels (c) and (d) show that R&D subsidy does not always stimulate innovation. Even though the timing of innovation by more efficient firms gets advanced (i.e., $\hat{X}_g(\hat{\lambda}_s^*)$ decreases in η), that of less efficient firms is rather delayed significantly in spite of the subsidies granted by the government (i.e., $\hat{X}_b(\hat{\lambda}_s^*)$ increases in η). This is because the optimal patent policy in the presence of R&D subsidy is chosen in favor of type g firm (i.e., $\hat{\lambda}_s^*(\eta)$ is closer to $1 - \eta/\delta_g$ than to $1 - \eta/\delta_b$), which results from the fact that type g contributes more to social welfare than type b does. Namely, the interaction between patent policy and R&D subsidy yields the different effects of R&D subsidy on the different types of innovators. This result is in line with Lach (2002) which provided empirical evidences of both positive and negative effects of R&D subsidies on the firms' R&D expenditure.

Traditional literatures have supported the government's R&D subsidy on the ground that it promotes innovation and mitigates the underinvestment problem (e.g., Nelson (1959), Arrow (1962)). In contrast, we have shown the possibility of its negative effects on both the timing of innovation and social welfare. The difference comes from the fact that we take into account the indirect effects from the patent protection policy adjusted in accordance with the subsidy. There are a large number papers that stressed the importance of having multiple instruments in R&D related policies,[15] and the extension of the model given in this section allows us to clarify the interaction between two policies on R&D investment.

To sum up, not only does R&D subsidy worsen the level of social welfare but also it rather delays the innovation of less efficient firms given the optimal patent protection. Thus, there is no reason to grant R&D subsidies under symmetric information unless the government wants to stimulate the innovation of more efficient firms at the expense of delay in that of less efficient ones

[15] Chu (2011) addressed the welfare cost of one-size-fits-all patent protection from the viewpoint of economic growth driven by innovation. Chu and Furukawa (2011) suggested the optimal mix of patent instruments, and Jeon and Nishihara (2017) proposed the optimal patent policy of two channels; probabilistic validity and damages rule. Chen (1991) introduced the tariff on foreign incumbents and R&D subsidies on domestic entrants, while Kang (2006) adopted a mix of IPR protection and R&D subsidies in the international R&D market.

and the losses in social welfare. There is a sharp contrast between this result and the argument from Kang (2006) which investigated the international R&D market. The author addressed that it is optimal to adopt weak IPR protection and to subsidize R&D investment, mainly because of the spillover effects between domestic and foreign firms. In contrast, we focused on a licensing game in vertically separated market with heterogeneous innovators and found that it is optimal to grant no subsidies and to guarantee full protection on patents under symmetric information. As will be shown shortly, however, information asymmetry changes the optimal policies as a mix of patent protection and R&D subsidy dramatically.

3.2 Asymmetric information

Now we shall examine if R&D subsidy is a suboptimal policy under asymmetric information as well. It is easy to check that the single crossing condition holds in the presence of R&D subsidy, and we can still adopt the framework of a signaling game based on the investment timing.

Following the same argument in Section 2.3, type b firm's incentive compatibility condition to mimic type g by investing at the threshold $\hat{X}$ is given as follows:

$$\left[\frac{\lambda\gamma_g c\hat{X}}{r-\mu} - \hat{\delta}_b\right]\left(\frac{x}{\hat{X}}\right)^{\alpha} \geq \left[\frac{\lambda\gamma_b c\hat{X}_b}{r-\mu} - \hat{\delta}_b\right]\left(\frac{x}{\hat{X}_b}\right)^{\alpha} = \hat{U}_b^s(x) \tag{35}$$

Similarly, type g firm's incentive compatibility condition to separate itself from type b is derived as follows:

$$\left[\frac{\lambda\gamma_g c\hat{X}}{r-\mu} - \hat{\delta}_g\right]\left(\frac{x}{\hat{X}}\right)^{\alpha} \geq \left[\frac{\lambda\gamma_b c\hat{X}_b}{r-\mu} - \hat{\delta}_g\right]\left(\frac{x}{\hat{X}_b}\right)^{\alpha} \tag{36}$$

Denoting the binding solutions of (35) and (36) by $\hat{X}^*$ and $\hat{X}^*_{\max}$, respectively, a separating equilibrium exists only if $\hat{X}^* \leq \hat{X}^*_{\max}$ holds.

In the presence of R&D subsidy $\eta \in (0, \delta_g)$, the value of the upstream and the downstream firms under asymmetric information can be obtained as follows:

$$\hat{U}_g^a(x) = \begin{cases} \left[\frac{\lambda\gamma_g c\hat{X}^*}{r-\mu} - \hat{\delta}_g\right]\left(\frac{x}{\hat{X}^*}\right)^{\alpha} & \text{if } \hat{X}^* < \hat{X}_g \\ \hat{U}_g^s(x) & \text{if } \hat{X}^* \geq \hat{X}_g \end{cases} \tag{37}$$

$$\hat{U}_b^a(x) = \hat{U}_b^s(x) \tag{38}$$

$$\hat{D}_g^a(x) = \begin{cases} \frac{(\pi-c)x}{r-\mu} + \left[\frac{(1-\lambda)\gamma_g c\hat{X}^*}{r-\mu}\right]\left(\frac{x}{\hat{X}^*}\right)^{\alpha} & \text{if } \hat{X}^* < \hat{X}_g \\ \hat{D}_g^s(x) & \text{if } \hat{X}^* \geq \hat{X}_g \end{cases} \tag{39}$$

$$\hat{D}_b^a(x) = \hat{D}_b^s(x) \tag{40}$$

The government's expenditure on R&D subsidy to each type of innovators is given by

$$\hat{S}_g^a(x) = \begin{cases} \eta\left(\frac{x}{\hat{X}^*}\right)^{\alpha} & \text{if } \hat{X}^* < \hat{X}_g \\ \hat{S}_g^s(x) & \text{if } \hat{X}^* \geq \hat{X}_g \end{cases} \tag{41}$$

$$\hat{S}_b^a(x) = \hat{S}_b^s(x) \tag{42}$$

and thus, social welfare is evaluated as follows:

$$\hat{W}^a(x) = p\hat{W}_g^a(x) + (1-p)\hat{W}_b^a(x) \tag{43}$$

where

$$\hat{W}_g^a(x) = \hat{U}_g^a(x) + \hat{D}_g^a(x) - \hat{S}_g^a(x) \tag{44}$$

$$= \begin{cases} \frac{(\pi-c)x}{r-\mu} + \left[\frac{\gamma_g c\hat{X}^*}{r-\mu} - \delta_g\right]\left(\frac{x}{\hat{X}^*}\right)^\alpha & \text{if } \hat{X}^* < \hat{X}_g \\ \hat{W}_g^s(x) & \text{if } \hat{X}^* \geq \hat{X}_g \end{cases} \tag{45}$$

$$\hat{W}_b^a(x) = \hat{W}_b^s(x) \tag{46}$$

As discussed in the previous subsection, the innovators make R&D investment decision based on the reduced costs $\hat{\delta}_i$ while the costs incurred in the society remain the same as δ_i for $i \in \{g, b\}$. The difference here, however, is that type g firm's investment decision depends on type b's incentive to mimic type g provided $\hat{X}^* < \hat{X}_g$ holds; (35) clearly shows that $\hat{X}^*$ is associated with $\hat{X}_b$ yet irrelevant to $\hat{X}_g$. This enables us to preserve the level of social welfare even in the presence of R&D subsidy as long as information asymmetry induces type g firm's overinvestment. This is in sharp contrast to the case of symmetric information under which social welfare strictly decreases in η.

To be more specific, we have $\hat{W}^a(x; \hat{\lambda}_a^*) = W^a(x; \lambda_a^*)$ provided $\hat{X}^* < \hat{X}_g$ and $X^* < X_g$ hold for $\hat{\lambda}_a^*(\eta)$ and λ_a^*, respectively, where $\hat{\lambda}_a^*(\eta)$ denotes the optimal patent protection that maximizes social welfare in (43). This is because we can align $\hat{X}_b(\lambda)$ with $X_b(\lambda_a^*)$ by having $\lambda = (1 - \eta/\delta_b)\lambda_a^*$, which matches $\hat{X}^*(\lambda)$ with $X^*(\lambda_a^*)$ as well. In this way, we can eliminate the inefficiency stemmed from the disparity of the decision-related costs and the actual costs incurred to society, and have the same level of social welfare as that without the subsidy.

For other cases, however, $\hat{W}^a(x; \hat{\lambda}_a^*) < W^a(x; \lambda_a^*)$ holds and the reason is as follows. Suppose $\hat{X}^* \geq \hat{X}_g$ and $X^* < X_g$ for $\hat{\lambda}_a^*(\eta)$ and λ_a^*, respectively. Type g firm invests at the threshold $\hat{X}_g$, not at $\hat{X}^*$, because it is the first-best investment trigger and type g can still separate itself from type b based on it. In this case, social welfare with R&D subsidy under asymmetric information coincides with that under symmetric information (i.e., $\hat{W}^a(x) = \hat{W}^s(x)$), which decreases in η. Thus, $\hat{W}^a(x; \hat{\lambda}_a^*) < W^a(x; \lambda_a^*)$ holds. When $X^* \geq X_g$, social welfare without R&D subsidy under asymmetric information coincides with that under symmetric information (i.e., $W^a(x) = W^s(x)$), and thus, $\hat{W}^a(x; \hat{\lambda}_a^*) < W^a(x; \lambda_a^*)$ holds regardless of the relationship between $\hat{X}^*$ and $\hat{X}_g$.

As discussed above, the argument changes dramatically depending on whether information asymmetry induces type g firm's overinvestment given the optimal patent policy (i.e., $\hat{X}^* < \hat{X}_g$ and $X^* < X_g$ for $\hat{\lambda}_a^*(\eta)$ and λ_a^*, respectively). We can derive the amount of subsidy η_a^* that makes type g firm's investment timing irrelevant to information structure (i.e., η_a^* equates $\hat{X}^*$ with $\hat{X}_g$) by solving the binding case of (35) with $\hat{X}_g$ instead of $\hat{X}$, which can be rearranged as follows:

$$\frac{\alpha\delta_g - (\alpha-1)\delta_b - \eta_a^*}{\delta_b - \eta_a^*} = \left(\frac{\gamma_b(\delta_g - \eta_a^*)}{\gamma_g(\delta_b - \eta_a^*)}\right)^\alpha \tag{47}$$

We can see from Panel (b) of Figure 2 that $\hat{W}^a(x; \hat{\lambda}_a^*)(= W^a(x; \lambda_a^*))$ is independent of η for $\eta \leq \eta_a^*$. For $\eta > \eta_a^*$, however, $\hat{W}^a(x; \hat{\lambda}_a^*)$ coincides with $\hat{W}^s(x; \hat{\lambda}_s^*)$ and decreases in η. Namely, we can have the first-best result under asymmetric information even in the presence of R&D subsidy unless the government grants too much subsidies. This stands in sharp opposition to

Gick (2008) which demonstrated that the government's subsidies on the costs of patent filing is socially wasteful under asymmetric information. Our model incorporates a two-channel policy of patent protection and R&D subsidy, and the interaction between them makes it possible to yield the first-best result even in the presence of the subsidy.

Panel (c) shows that the gap between $\hat{X}^*(\hat{\lambda}_a^*)$ and $\hat{X}_g(\hat{\lambda}_a^*)$ monotonically decreases in η for $\eta \leq \eta_a^*$. That is, R&D subsidy reduces the inefficiency in type g firm's investment decision induced by information asymmetry unless too much subsidies are given. This is because as the amount of R&D grants increases, relative differences in the cost efficiency between the firms increases, which makes type b less willing to mimic type g's investment decision. This proper function of R&D subsidy makes $\hat{W}^a(x;\hat{\lambda}_a^*)$ not to decrease in η for $\eta \leq \eta_a^*$. For $\eta > \eta_a^*$, however, type b firm would not mimic type g even if type g invests at its first-best timing (i.e., $\hat{X}_g(\hat{\lambda}_a^*)$). Thus, the proper function of disincentivizing less efficient firm's mimicking is lost while the disparity in the decision-related costs and the actual costs incurred to society remains, which leads to the decrease in social welfare.

Even though R&D subsidy reduces the inefficiency in type g's investment stemmed from information asymmetry, the timing of actual innovation of both firms does not change unless too much subsidies are granted. Namely, only $\hat{X}_g(\hat{\lambda}_a^*)$ decreases in η while $\hat{X}^*(\hat{\lambda}_a^*)$ and $\hat{X}_b(\lambda_a^*)$ remain the same for $\eta \leq \eta_a^*$ (Panels (c) and (d) of Figure 2). This is in sharp contrast to the result from Section 3.1; under symmetric information, R&D grants always stimulate more efficient firms' innovation (i.e., $\hat{X}_g(\hat{\lambda}_s^*)$ strictly decreases in η) even though it is made at the costs of delay in less efficient firms' R&D and the decrease in social welfare (i.e., $\hat{X}_b(\hat{\lambda}_s^*)$ and $\hat{W}^s(\hat{\lambda}_s^*)$ strictly increases and decreases in η, respectively).

The fact that R&D subsidy does not guarantee the stimulation of R&D investment is consistent with many empirical evidences of insignificant correlation between the subsidy and R&D investment. For instance, Wallsten (2000) and Klette and Møen (2012) found that the subsidized firms did not raise their R&D activity nor did they cut it back. Other studies have witnessed evidences of publicly funded R&D crowding out privately funded R&D in that total amount of R&D projects does not change in spite of the grants (e.g., Busom (2000), Klette, Møen, and Griliches (2000), David, Hall, and Toole (2000)), which corresponds to no change in the investment timing in our model. Excessive R&D grants (i.e., $\eta > \eta^*$) can advance the timing of innovation of more efficient firms under asymmetric information as well, but it also involves the delay in less efficient firms' innovation and the losses in social welfare.

So far, we have discussed how R&D subsidy affects the firm's investment decision under asymmetric information. We also need to investigate how information asymmetry changes the timing of innovation in the presence of R&D subsidy. We can see from Panels (c) and (d) of Figure 2 that given the subsidy, more efficient firms innovate earlier under asymmetric information (i.e., $\min(\hat{X}_g(\hat{\lambda}_a^*), \hat{X}^*(\hat{\lambda}_a^*)) \leq \hat{X}_g(\hat{\lambda}_s^*)$) while less efficient ones delay their R&D investment (i.e., $\hat{X}_b(\hat{\lambda}_a^*) \geq \hat{X}_b(\hat{\lambda}_s^*)$). This is in contrast to the result from Section 2.3; in the absence of R&D grants, the effects of asymmetric information on type g firm's investment is not clear (i.e., either $X^*(\lambda_a^*) < X_g(\lambda_s^*)(< X_g(\lambda_a^*))$ or $X_g(\lambda_s^*) < \min(X^*(\lambda_a^*), X_g(\lambda_a^*))$ can hold) whereas it always delays type b's R&D (i.e., $X_b(\lambda_a^*) > X_b(\lambda_s^*)$ always holds). That is, the effects of information asymmetry on the timing of innovation becomes even clearer in the presence of R&D subsidy.

Meanwhile, Panel (a) of Figure 2 shows that $\hat{\lambda}_a^*$ decreases in η as well but its slope is gentler than that of $\hat{\lambda}_s^*$ for $\eta \leq \eta_a^*$. That is, for an increment of R&D subsidy, the government should lower less protection on patent rights under asymmetric information than it should under symmetric information. This is also because of R&D subsidy's proper functioning of disincentivizing type b firm's mimicking, which makes the government afford more protection on patent rights (recall that perfect protection is optimal when information is symmetric and no grants are given). When too much subsidies are granted, however, the benefits of having them is dominated by their costs, and the optimal patent policy under asymmetric information coincides with that under symmetric information (i.e., $\hat{\lambda}_s^* = \hat{\lambda}_a^*$ for $\eta > \eta_a^*$).

The fact that $\hat{W}^a(x; \hat{\lambda}_a^*)$ does not decrease in η for $\eta \leq \eta_a^*$ can play a crucial role in making policies for different industries with different asymmetry between innovators. Suppose there are two industries; A and B. It is needless to say that the optimal patent protection for each industry, denoted by λ_a^{n*} for $n \in \{A, B\}$, differs from each other; we assume $\lambda_a^{A*} < \lambda_a^{B*}$ without loss of generality. The government can maximize social welfare in both industries by setting the level of patent protection as λ_a^{A*} and granting R&D subsidy η_a^B to the innovators in B industry in which insufficient protection is given on patents such that $\hat{\lambda}_a^{B*}(\eta_a^B)$ yields the first-best result $\hat{W}_B^a(x; \hat{\lambda}_a^{B*}) = W_B^a(x; \lambda_a^{B*})$. That is, the R&D subsidy granted to B industry, η_a^B, needs to be chosen such that $\lambda_a^{A*} = \hat{\lambda}_a^{B*}(\eta_a^B)$ holds. These policies can induce the first-best results in both industries as long as $\eta_a^B < \eta_a^{B*}$ holds where η_a^{B*} denotes the solution of (47) for B industry. Note that the level of patent protection is chosen as the lower one between the optimal patent policies for each industry. This is because R&D subsidy cannot disincentivize when innovators are overprotected by patent rights.

One can easily see that this argument can be extended to the policies of patent protection and R&D subsidy for more than three industries. As discussed above, the level of patent protection decreases in the number of industries to which the patent policy is applied. This result can account the government's mild protection on patent rights in the real world and is consistent with empirical evidences of a great deal of invalidated patents.[16]

4 Comparative statics and discussion

4.1 Parameters

We adopt the following parameters as a benchmark case for comparative statics:

$$r = 0.05, \quad \mu = 0.02, \quad \sigma = 0.2, \quad \pi = 1, \quad c = 1, \quad x = 0.1$$
$$p = 0.5, \quad \gamma_g = 2/3, \quad \gamma_b = 1/3, \quad \delta_g = 2, \quad \delta_b = 3$$

We suppose $\pi = c$, which implies perfect competition in the downstream market. Namely, the downstream firm can only make positive profits with the cost-saving technology invented by the

[16] Allison and Lemley (1998) and Moore (2000) found that roughly a half of litigated patents are found invalid by the court's ruling.

upstream firm. In terms of asymmetry in the upstream market, the innovator is equally probable to be type g and type b. The difference between the innovators in terms of the technology's quality and R&D cost efficiency is set at our own discretion, but the results are found robust with respect to those parameters.

4.2 Asymmetry in technology's quality

First of all, we examine how the optimal patent protection and the maximum amount of R&D subsidy that can yield the first-best result vary with respect to the difference in the technology's quality. We fix γ_b and see how the results change as γ_g increases.

Insert Figure 3 here.

We can see from Panel (b) of Figure 3 that λ_a^*, the optimal patent protection under asymmetric information, decreases in γ_g. Namely, the government should loosen the protection on patent rights when there is a significant difference between the innovators' technology quality. Given higher royalties for more innovative technology, type b firm is more willing to mimic type g when γ_g is much higher than γ_b, which makes type g deviate more from its first-best investment timing. Therefore, the government needs to curb type b's incentive to mimic type g by lowering λ so that the losses from type g's inefficient investment decision are mitigated. This leads to the decrease of the gap between X^* and X_g in Panel (c).

Panel (a) shows that η_a^*, the maximum amount of R&D subsidy with which the government can yield the first-best result under asymmetric information, increases in γ_g. This is because the subsidy's proper function of disincentivizing type b to mimic type g is worth more when the difference between technology's quality is significant. Given higher η_a^*, the government has more options in policies to maximize social welfare; the combination of η and $\hat{\lambda}_a^*(\eta)$ that induces the first-best result increases in γ_g because $W^a(x;\lambda_a^*) = \hat{W}^a(x;\hat{\lambda}_a^*)$ holds for $\eta \leq \eta_a^*$.

Panel (b) also describes $\hat{\lambda}_a^*(\eta_a^*)$ and we can clearly see $\hat{\lambda}_a^*(\eta_a^*) < \lambda_a^*$. This is a natural result because both patent protection and R&D subsidy are the policies to incentivize innovation and the government should not overcompensate the inventors. The gap between λ_a^* and $\hat{\lambda}_a^*(\eta_a^*)$ implies that the government can lower the level of patent protection from λ_a^* up to $\hat{\lambda}_a^*(\eta_a^*)$ by granting R&D subsidy while preserving the first-best result in terms of social welfare.

For the optimal policy of patent protection and R&D subsidy applied to multiple industries, the government should set the level of patent protection as the first-best one for the industry with the sharpest difference in technology's quality and grant R&D subsidy to other industries in which the difference is less significant. Yet, we can see from Panel (b) that λ_a^* with sufficiently high γ_g is lower than $\hat{\lambda}_a^*(\eta_a^*)$ with sufficiently low γ_g, which is mainly because η_a^* increases in γ_g. In the example of two industries in Section 3.2, this corresponds to $\lambda_a^{A*} < \hat{\lambda}_a^{B*}(\eta_a^{B*})$. This implies that the optimal policy might not be able to induce the first-best result in every industry if each industry's degree of asymmetry in terms of technology's quality differs significantly.

4.3 Asymmetry in R&D cost efficiency

Now we proceed to the analysis on the optimal policies for a different level of asymmetry in R&D efficiency. We fix δ_g and see how the argument changes as δ_b increases.

Insert Figure 4 here.

We can see from Panel (b) of Figure 4 that λ_a^* increases in δ_b. Namely, the government needs to strengthen the patent protection when there is a significant difference between innovators in terms of R&D costs. As δ_b increases, type b firm is less willing to mimic type g's investment decision because of higher costs of distortion in the investment timing. Therefore, the government can afford more protection on patent rights as the difference between the innovators' R&D costs becomes significant.

Panel (a) shows that η_a^* decreases in δ_b. That is, the maximum amount of R&D subsidy that can yield the first-best result under asymmetric information decreases as the difference in R&D efficiency becomes more significant. As mentioned above, type b firm's incentive to mimic type g's investment behavior decreases in δ_b, which makes the subsidy's proper function of disincentivizing the mimicking less significant. Therefore, when the gap between R&D costs is significant, the government has less combination of η and $\hat{\lambda}_a^*(\eta)$ to induce the first-best result in terms of social welfare.

Given these results, we can claim that the optimal policy of patent protection and R&D subsidy under asymmetric information converges to that under symmetric information (i.e., $\eta_s^* = 0$ and $\lambda_s^* = 1$) as the difference in R&D costs increases. This is in sharp contrast to the results from Section 4.1; in terms of the difference in technology's quality, the optimal policy under asymmetric information converges to that under symmetric information as the difference decreases. This is because the difference in technology's quality and that in R&D cost efficiency work in the opposite direction. Type b is more willing to mimic type g when the gap between technology's quality is significant, whereas it is less willing to do so when the difference in R&D efficiency is less significant.

For the optimal policy of patent protection and R&D subsidy applied to multiple industries, the government needs to set the patent protection as the first-best level for the industry with the least difference in R&D costs and grant subsidies to other industries with more significant difference in R&D costs. Yet, we can see from Panel (b) that λ_a^* with sufficiently low δ_b can be lower than $\hat{\lambda}_a^*(\eta_a^*)$ with sufficiently high δ_b. This result mainly comes from the fact that η_a^* decreases in δ_b and implies that the optimal policy might not be able to induce the first-best result in every industry if there is a huge difference in each industry's R&D cost efficiency.

4.4 Proportion of more efficient firms

Lastly, we examine how the proportion of more efficient firms in upstream market, p, affects the optimal policy of patent protection and R&D subsidy.

Insert Figure 5 here.

We can see from Panel (b) of Figure 5 that λ_a^* decreases in p. That is, the government should lower the level of patent protection when the number of more efficient innovators dominate that of less efficient ones. This is because the downstream firm's gain from earlier innovation increases in the number of more innovative firms. Thus, in spite of the type g firm's losses from inefficient investment timing, the government needs to loosen patent protection to maximize the gains from the downstream market.

Panel (a) shows that η_a^* is independent of p. Namely, the amount of maximum subsidy to R&D projects is regardless of how many firms are more efficient than others. This is because type b firm's incentive to mimic type g firm is regardless of the proportion of more innovative firms, which can be clearly seen from (47). Note that λ_a^* decreases in p not because type b is more willing to mimic type g when there are more efficient firms in the upstream market but because the gains from earlier innovation increases in p.

In terms of the optimal policy for multiple industries, patent protection level should be set as the first-best one for the industry with the most number of more innovative firms and R&D subsidy should be granted to other industries. We can see from Panel (b) that for the benchmark parameters, λ_a^* with $p = 1$ is higher than $\hat{\lambda}_a^*(\eta_a^*)$ with $p = 0$. In the example of two industries in Section 3.2, this corresponds to $\lambda_a^{A*} = \hat{\lambda}_a^{B*}(\eta_a^B)$ for $\eta_a^B \leq \eta_a^{B*}$, and this is mainly because η_a^* is independent of p. Thus, given enough differences between the upstream firms, the government can induce the first-best result for every industry regardless of the proportion of more innovative firms in each industry.

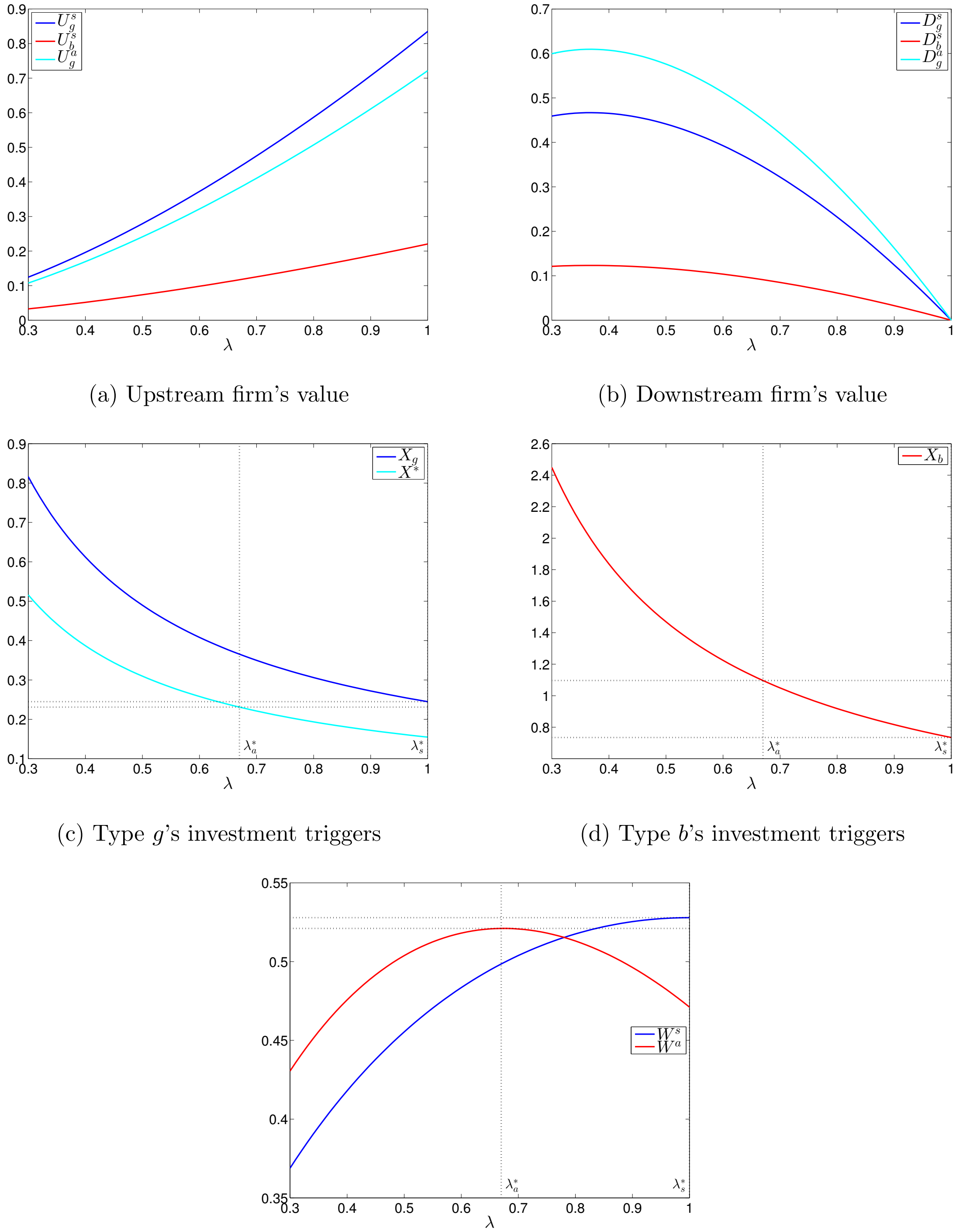
5 Conclusion

In this paper, we have investigated a licensing contract of vertically separated market under asymmetric information based on a signaling game via investment timing. Less efficient innovators are willing to mimic more efficient ones' behavior for the sake of higher royalties. This makes the dominant innovator invests earlier than it would have made under symmetric information to separate itself from the dominated one.

We have shown that perfect patent protection is the optimal policy under symmetric information, whereas it is not under asymmetric information. Furthermore, social welfare under asymmetric information can be higher than that under symmetric information for most patent protection level. Given the optimal patent policy for each regime, however, the latter dominates the former. We also incorporate R&D subsidy as another axis of R&D policies along with the patent protection, and it is found suboptimal under symmetric information while it can be optimal in the presence of information asymmetry. The subsidy can stimulate the R&D investment of more efficient innovators under symmetric information, but it can only be made at the expenses of the delay of less efficient ones' investment and the losses of social welfare. Under asymmetric information, however, it neither stimulates nor stifiles innovation unless too much is given. Information asymmetry yields underinvestment of less efficient innovators and overinvestment of more efficient ones, especially when the subsidy is granted. Last but not least, we have derived the optimal policy of two channels that can yield the first-best results in multiple industries at the same time.

The framework of a signaling via investment timing enabled us to shed light on the dynamics perspective of licensing games. There are, however, a number of problems that remain to be explored. For instance, bilateral information asymmetry can exist in the market; not only cannot manufacturers identify the quality of innovators' technologies but also inventors are not informed about the counterparty's profitability. The competition in the downstream market can also change the arguments dramatically. It is to be hoped that this paper serves as a platform for future research on these issues.

A Figures



(a) Upstream firm's value

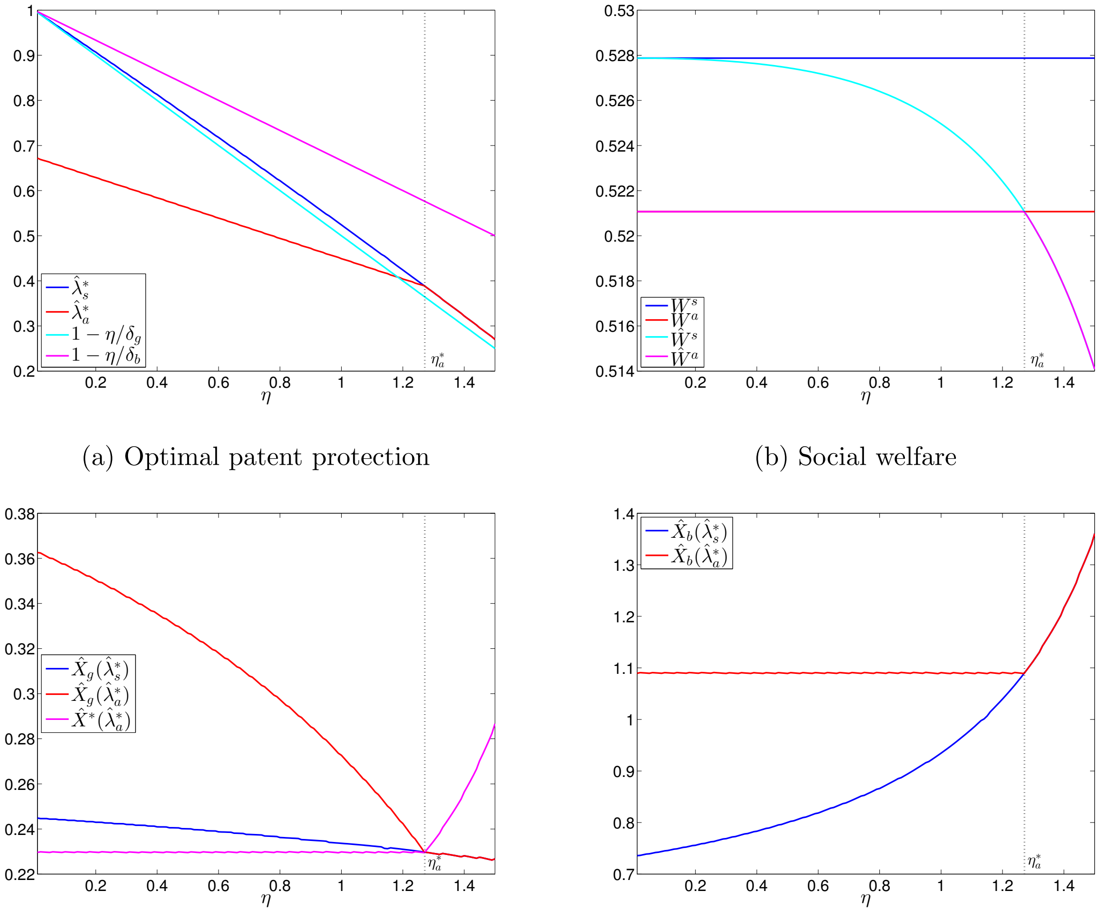
(b) Downstream firm's value

(c) Type g's investment triggers

(d) Type b's investment triggers

(e) Social welfare

Figure 1: Comparative statics with respect to the level of patent protection under symmetric and asymmetric information



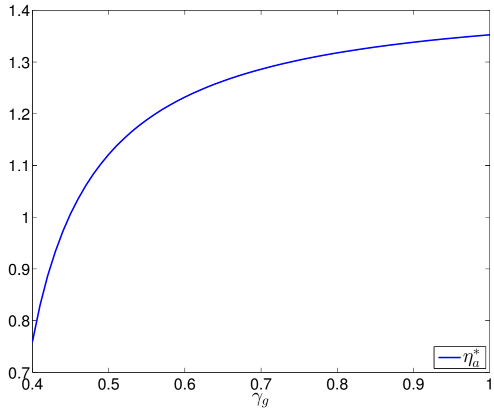
(a) Optimal patent protection

(b) Social welfare

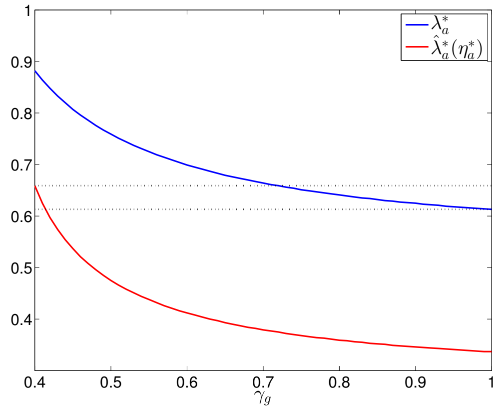
(c) Type g's investment triggers

(d) Type b's investment triggers

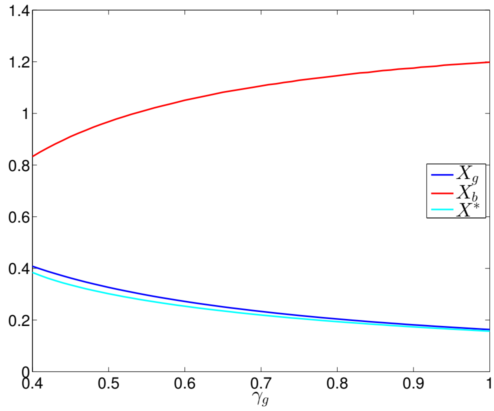
Figure 2: Comparative statics with respect to R&D subsidy under symmetric and asymmetric information



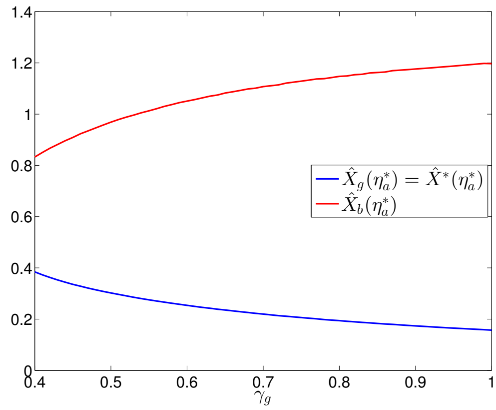
(a) Maximum amount of R&D subsidy that can yield the first-best result



(b) Optimal patent protection with and without R&D subsidy

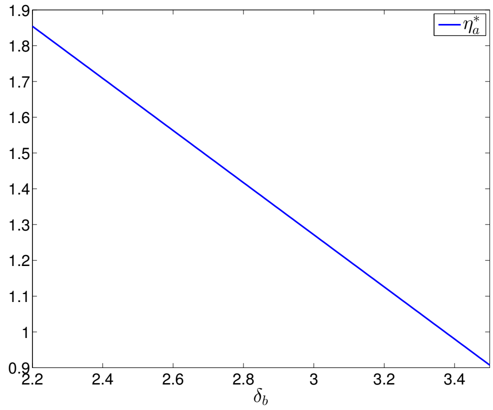


(c) Investment triggers without R&D subsidy

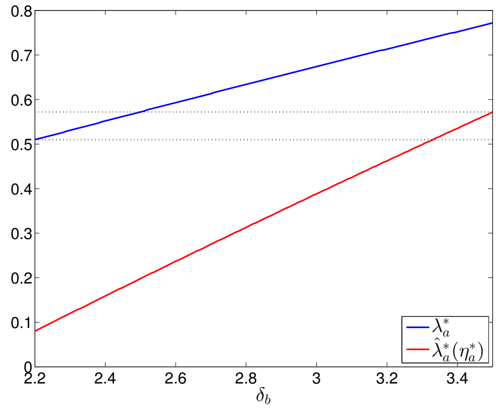


(d) Investment triggers with R&D subsidy

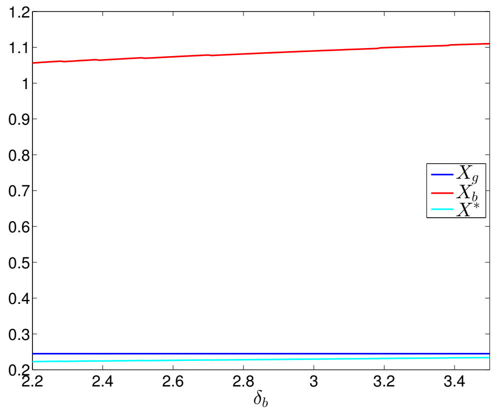
Figure 3: Comparative statics with respect to the technology's quality under asymmetric information



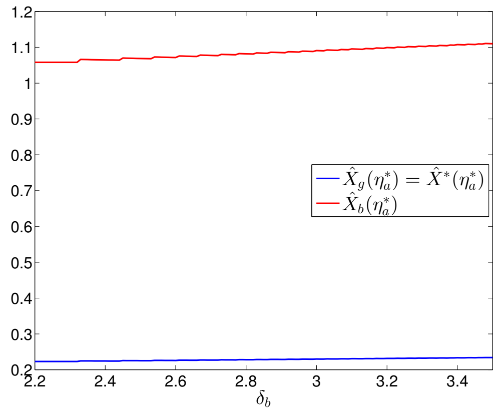
(a) Maximum amount of R&D subsidy that can yield the first-best result



(b) Optimal patent protection with and without R&D subsidy

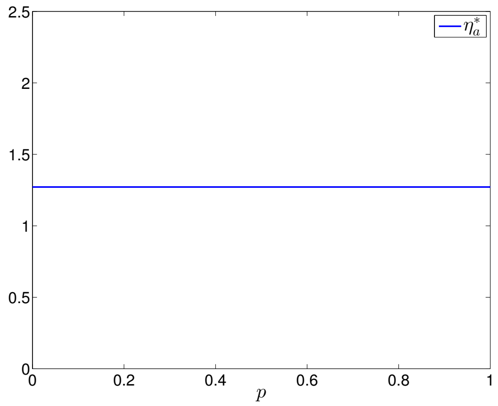


(c) Investment triggers without R&D subsidy

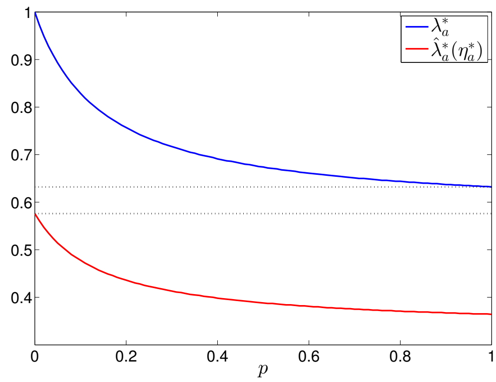


(d) Investment triggers with R&D subsidy

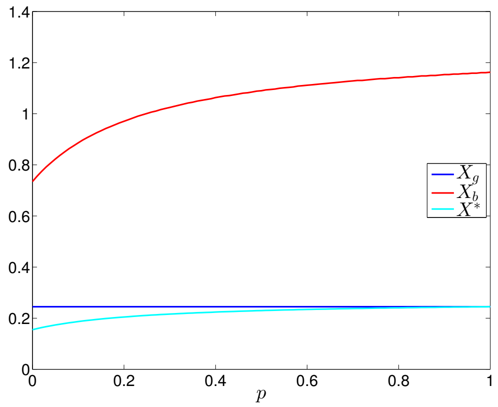
Figure 4: Comparative statics with respect to the R&D cost efficiency under asymmetric information



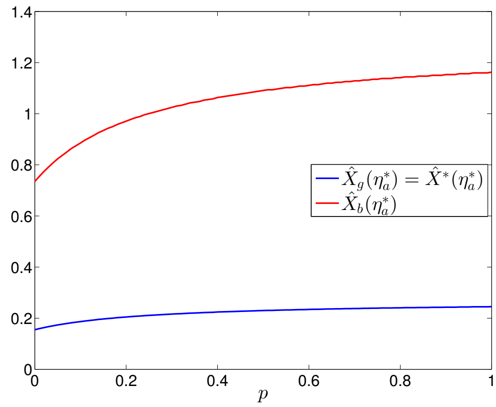
(a) Maximum amount of R&D subsidy that can yield the first-best result



(b) Optimal patent protection with and without R&D subsidy



(c) Investment triggers without R&D subsidy



(d) Investment triggers with R&D subsidy

Figure 5: Comparative statics with respect to the proportion of more innovative firms in upstream market under asymmetric information

References

Allison, J., and M. Lemley, 1998, Empirical analysis of the validity of litigated patents, *American Intellectual Property Law Association Quarterly Journal* 26, 185–275.

Anton, J., and D. Yao, 1994, Expropriation and inventions: Appropriable rents in the absence of property rights, *American Economic Review* 84, 190–209.

——— , 2002, The sale of ideas: strategic disclosure, property rights, and contracting, *Review of Economic Studies* 69, 513–531.

——— , 2003, Patents, invalidity, and the strategic transmission of enabling information, *Journal of Economics and Management Strategy* 12, 151–178.

——— , 2004, Little patents and big secrets: managing intellectual property, *RAND Journal of Economics* 35, 1–22.

——— , 2006, Finding “lost” profits: An equilibrium analysis of patent infringement damages, *Journal of Law, Economics, and Organization* 23, 186–207.

Aoki, R., and J. Hu, 1999, Licensing vs. litigation: The effect of the legal system on incentives to innovate, *Journal of Economics and Management Strategy* 8, 133–160.

Arrow, K., 1962, Economic welfare and the allocation of resources for invention, in *The Rate and Direction of Inventive Activity* . pp. 609–626 (Princeton University Press).

Beggs, A., 1992, The licensing of patents under asymmetric information, *International Journal of Industrial Organization* 10, 171–191.

Bessen, J., 2004, Holdup and licensing of cumulative innovations with private information, *Economic Letters* 82, 321–326.

Bhattacharya, S., and J. Ritter, 1983, Innovation and communication: Signalling with partial disclosure, *Review of Economic Studies* 50, 331–346.

Brander, J., and B. Spencer, 1983, Strategic commitment with R&D: the symmetric case, *Bell Journal of Economics* 14, 225–235.

Busom, I., 2000, An empirical evaluation of the effects of R&D subsidies, *Economics of Innovation and New Technology* 9, 111–148.

Bustamante, M., 2012, The dynamics of going public, *Review of Finance* 16, 577–618.

Chang, H., 1995, Patent scope, antitrust policy, and cumulative innovation, *RAND Journal of Economics* 26, 34–57.

Chen, M., 1991, The role of R&D subsidies when incomplete information is an entry-barrier, *Journal of International Economics* 31, 251–270.

Cho, I., and D. Kreps, 1987, Signaling games and stable equilibria, *Quarterly Journal of Economics* 102, 179–221.

Choi, J., 1998, Patent litigation as an information-transmission mechanism, *American Economic Review* 88, 1249–1263.

——— , 2009, Alternative damage rules and probabilistic intellectual property rights: Unjust enrichment, lost profits, and reasonable royalty remedies, *Information Economics and Policy* 21, 145–157.

Chu, A., 2011, The welfare cost of one-size-fits-all patent protection, *Journal of Economics Dynamics and Control* 35, 876–890.

——— , and Y. Furukawa, 2011, On the optimal mix of patent instruments, *Journal of Economics Dynamics and Control* 35, 1964–1975.

Czarnitzki, D., and A. Toole, 2007, Business R&D and the interplay of R&D subsidies and product market uncertainty, *Review of Industrial Organization* 31, 169–181.

David, P., B. Hall, and A. Toole, 2000, Is public R&D a complement or substitute for private R&D? a review of the econometric evidence, *Research Policy* 29, 497–529.

Denicolò, V., 1996, Patent races and optimal patent breadth and length, *Journal of Industrial Economics* 44, 249–265.

Farrell, J., and C. Shapiro, 2008, How strong are weak patents?, *American Economic Review* 98, 1347–1369.

Fudenberg, D., and J. Tirole, 1991, *Game Theory* (MIT Press: Cambridge).

Gallini, N., and B. Wright, 1990, Technology transfer under asymmetric information, *RAND Journal of Economics* 21, 147–160.

Gick, W., 2008, Little firms and big patents: A model of small-firm patent signaling, *Journal of Economics and Management Strategy* 17, 913–935.

Gilbert, R., and C. Shapiro, 1990, Optimal patent length and breadth, *RAND Journal of Economics* 21, 106–112.

González, X., and C. Pazó, 2008, Do public subsidies stimulate private R&D spending?, *Research Policy* 37, 371–389.

Green, J., and S. Scotchmer, 1995, On the division of profit in sequential innovation, *RAND Journal of Economics* 26, 20–33.

Grenadier, S., and A. Malenko, 2011, Real options signaling games with applications to corporate finance, *Review of Financial Studies* 24, 3993–4036.

Grossman, G., and H. Horn, 1988, Infant industry protection reconsidered: The case of informational barriers to entry, *Quarterly Journal of Economics* 103, 767–787.

Hall, B., 2002, The financing of research and development, *Oxford Review of Economic Policy* 18, 35–51.

Hinloopen, J., 1997, Subsidizing cooperative and noncooperative R&D in duopoly with spillovers, *Journal of Economics* 66, 151–175.

Hsu, Y., and B. Lambrecht, 2007, Preemptive patenting under uncertainty and asymmetric information, *Annals of Operations Research* 151, 5–28.

Hussinger, K., 2008, R&D and subsidies at the firm level: an application of parametric and semiparametric two-step selection models, *Journal of Applied Econometrics* 23, 729–747.

Jeon, H., and M. Nishihara, 2017, Optimal patent policy in the presence of vertical separation, Working paper.

Kang, M., 2006, Trade policy mix: IPR protection and R&D subsidies, *Canadian Journal of Economics* 39, 744–757.

Klemperer, P., 1990, How broad should the scope of patent protection be?, *RAND Journal of Economics* 21, 113–130.

Klette, T., and J. Møen, 2012, R&D investment responses to R&D subsidies: a theoretical analysis and a microeconometric study, *World Review of Science, Technology and Sustainable Development* 9, 169–203.

——— , and Z. Griliches, 2000, Do subsidies to commercial R&D reduce market failures? microeconometric evaluation studies, *Research Policy* 29, 471–495.

Lach, S., 2002, Do R&D subsidies stimulate or displace private R&D? evidence from Israel, *Journal of Industrial Economics* 50, 369–390.

Lahiri, S., and Y. Ono, 1999, R&D subsidies under asymmetric duopoly: a note, *Japanese Economic Review* 50, 104–111.

Leahy, D., and J. Neary, 1997, Public policy towards R&D in oligopolistic industries, *America Economic Review* 87, 642–662.

Lerner, J., 1999, The government as venture capitalist: the long-run impact of the SBIR program, *Journal of Business* 72, 285–318.

——— , and J. Tirole, 2004, Efficient patent pools, *American Economic Review* 94, 691–711.

Leung, C., and Y. Kwok, 2011, Real options game analysis of sleeping patents, *Decisions in Economics and Finance* 34, 41–65.

Martimort, D., J. Poudou, and W. Sand-Zantman, 2010, Contracting for an innovation under bilateral asymmetric information, *Journal of Industrial Economics* 58, 324–348.

Miltersen, K., and E. Schwartz, 2004, R&D investments with competitive interactions, *Review of Finance* 8, 355–401.

Moore, K., 2000, Judges, juries, and patent cases: An empirical peek inside the black box, *Michigan Law Review* 99, 365–409.

Morellec, E., and N. Schürhoff, 2011, Corporate investment and financing under asymmetric information, *Journal of Financial Economics* 99, 262–288.

Nelson, R., 1959, The simple economics of basic scientific research, *Journal of Political Economy* 67, 297–306.

Schmitz, P., 2002, On monopolistic licensing strategies under asymmetric information, *Journal of Economic Theory* 106, 177–189.

Scotchmer, S., 1991, Standing on the shoulders of giants: Cumulative research and the patent law, *Journal of Economic Perspectives* 5, 29–41.

——— , 1996, Protecting early innovators: Should second-generation products be patentable?, *RAND Journal of Economics* 27, 322–331.

Shapiro, C., 2008, Patent reform: Aligning reward and contribution, in A. Jaffe, J. Lerner, and S. Stern, ed.: *Innovation Policy and the Economy* . pp. 111–156 (University of Chicago Press).

Shepard, A., 1987, Licensing to enhance demand for new technologies, *RAND Journal of Economics* 18, 360–368.

Spence, M., 1984, Cost reduction, competition, and industry performance, *Econometrica* 52, 101–121.

Wallsten, S., 2000, The effects of government-industry R&D programs on private R&D: the case of the Small Business Innovation Research program, *RAND Journal of Economics* 31, 82–100.

Wright, D., 1999, Optimal patent breadth and length with costly innovation, *International Journal of Industrial Organization* 17, 419–436.