数理解析研究所講究録 第2106巻 2019年 1-17

Innovation Timing and Information Disclosure[1]

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1 Introduction

In this paper, we investigate a license contract of a vertically separated market in the presence of asymmetric information and competition. An upstream firm wants to conclude a license contract for its patented technology with a downstream firm, but a follower can challenge the technology at some point, and the downstream firm does not know how long the monopoly of the patented technology will last. Upon challenge, the patent holder files a lawsuit over infringement, and the court's ruling is based on the technology's true novelty. If the leader wins the trial, it maintains the monopolistic position in the market, but it can lose the case and start competing with the follower. In this sense, the probability that the patentee wins the trial is directly linked to the value of the patented technology, which only the innovator knows.

First, we show that an innovator with more valuable technology voluntarily discloses its private information about the invention despite the rival's earlier challenge, whereas the one with less valuable technology reveals nothing. This result is in line with theoretical analyses of Gick (2008) and Anton and Yao (2002, 2008). The former, which examined signaling via patent disclosure, lacked an explanation of how exactly the disclosure incurs costs to the innovators, and the latter studied the sales of idea in the presence of downstream competition based on a static model. In contrast, we clarify the cost of information disclosure by incorporating the follower's challenge and examine the interaction between the decisions of information disclosure and investment timing based on a continuous-time dynamic model. This finding is also consistent with empirical evidence from Graham and Hegde (2015), who investigate inventors' disclosure strategy before and after the American Inventors Protection Act (AIPA), which requires U.S. patent applications to be made public within 18 months from the filing date, except for those without a parallel foreign filing. They show that a surprisingly large portion of applicants who could have opted out of the 18-month publication enforcement actually chose pre-grant disclosure over pre-grant secrecy.

Furthermore, we show that innovators overinvest in R&D under asymmetric information. Given the follower's earlier challenge induced by information disclosure, the leader makes an R&D investment earlier than it would have under symmetric information, not only because it can raise more revenue before the rival challenges but also because earlier investment lowers the amount of information disclosure for more valuable technology. This result is in contrast to the conventional wisdom that the need to disclose complementary information such as pre-grant publication will retard innovation. Aoki and Spiegel (2009) examine the impact of pre-

[1]This paper is an abbreviated version of Jeon (2018), and was supported by the JSPS KAKENHI (Grant number 17K13728).

grant publication in the presence of cumulative innovation and claim that it will lead to fewer inventions. Gans et al. (2008) focus on the impact of uncertainty during patent pendency, and show that the hazard rate of achieving a license significantly increases after patents are granted. We analyze the interaction between the decisions of information disclosure and investment timing from the dynamics perspective, and show that the need to disclose private information puts the timing of innovation forward.

Regarding the extent of information disclosure, we find that the more valuable the technology is and the less bargaining power the innovator has, the more private information its owner discloses. This result is in line with theoretical analysis by Anton and Yao (2002, 2008) and empirical evidence from Graham and Hegde (2015). The former investigates the sale of ideas with downstream competition and showed that the amount of disclosure increases with the idea's value. The latter finds that the probability of choosing pre-grant secrecy over pre-grant publication decreases with the value of patents, especially for small inventors. Our model also shows that the stronger the follower's challenge is, the more private information the leader discloses. The follower challenges earlier when its technology substitutes the leader's one to a larger extent. Given the imminent challenge, a leader with less valuable technology has more incentive to pretend that it has more valuable one. Thus, the owner of more innovative technology has to disclose more information to separate itself from the owner of less valuable one, which worsens the leader's firm value.

Lastly, we show that even though the leading innovator suffers losses from information disclosure, total value of the firms in the market may increase under asymmetric information due to the diffusion of knowledge. The follower can refer to the disclosed information for its own R&D and save costs for duplicative R&D, which is socially beneficial. As a whole, the benefits from R&D spillover can dominate the leader's losses. This result supports the requirement of pre-grant publication upon patent application. Cohen et al. (2002) conducted national surveys in the U.S. and Japan, and found that though innovators' appropriability is lower, R&D spillovers are significantly greater in Japan, where the patent system focuses more on the diffusion of technology. This suggests that a diffusion-oriented patent system can benefit society as a whole.

2 Models and solutions

2.1 Setup

Suppose there is an upstream leader that can develop new technology and acquire a patent at a lump-sum cost c_L. A product based on this technology yields revenue flow $\pi_M X_t$ with a constant π_M and a demand shock X_t given by a one-dimensional geometric Brownian motion as follows:

$$\mathrm{d}X_t = \mu X_t \mathrm{d}t + \sigma X_t \mathrm{d}W_t, \tag{2.1}$$

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 $r > \mu$ for the finiteness of the value functions. The upstream firm, however, does not have its own manufacturing facilities, and has to arrange a license contract with a downstream firm to profit from the patented technology. Upon the contract, the bargaining power of the upstream and downstream firms are given by β and $1-\beta$, respectively, where $\beta \in [0,1]$.

In spite of the right to monopolize the market, there can be a challenge against it. Namely, an upstream follower can invent around the patented technology, or even make better technology that makes the leader's technology obsolete, at a cost c_F. The upstream follower does not have its own manufacturing facilities either, and has to license it to another downstream firm, a downstream follower. Upon this challenge, the leader files a lawsuit, claiming that the follower has infringed the patent rights. The patentee wins the trial with probability $p \in (0,1)$ and maintains its monopolistic position in the market. With probability $1-p$, however, it loses the case; the patent is invalidated by the court's ruling and they start competing with each other in the market. Given the duopoly, products based on the technologies of the upstream leader and follower make revenue flows $\pi_D^L X_t$ and $\pi_D^F X_t$, respectively, where $\pi_D := \pi_D^L + \pi_D^F \leq \pi_M$.

We can interpret p as the novelty of the leader's technology. As Lemley and Shapiro (2005) note, the overwhelming majority of patent applications in the U.S. ultimately result in an issued patent and the true novelty of patented technology is examined thoroughly when litigation is involved. It can also be read as the technology's value because the innovator's appropriability can be measured based on how long it takes for rivals to imitate a firm's innovation (e.g., Levin et al. (1987)), and the follower will challenge later for higher p in our model. We suppose there are two types of leader's technology; type g and type b, the patents on which win the trial with probability p_g and p_b, respectively, where $p_g > p_b$. The true novelty, however, is not known to other parties. Even the innovator can only identify it after the R&D investment. Namely, the leader makes an R&D investment timing decision without knowing the profitability, and it is realized as type g and type b with probability q and $1-q$, respectively, where $q \in (0,1)$.

2.2 Benchmark model: symmetric information

Suppose that the upstream leader acquired patents on its technology of type $i \in \{g, b\}$ and arranged a license contract with the downstream leader. Based on the existing technology, the upstream follower can imitate, or even make better technology that makes the leader's technology obsolete, at a cost c_F. Due to the lack of production facilities, the upstream follower also has to make a license contract and share profits with the downstream follower. Upon the rival's challenge, the leader files a lawsuit over infringement and wins the trial with probability p_i. In other words, the followers can only make profits with probability $1-p_i$. Thus, given the investment and the license contract, the upstream and downstream followers challenging the leader's type i technology share the following revenue with each other:

$$\mathbb{E}\Big[\int_t^\infty e^{-r(s-t)}(1-p_i)\pi_D^F X_s \mathrm{d}s \Big| X_t = x\Big] = \frac{(1-p_i)\pi_D^F x}{r-\mu}. \tag{2.2}$$

Because both the upstream and downstream followers do not have outside options in their bargaining, the sharing rule is directly linked to their bargaining power, β and $1-\beta$, respectively.[2]

[2]We suppose the bargaining power of the upstream and downstream firms is irrelevant to their position in the market. Namely, both the upstream leader and follower have a bargaining power of β, while the downstream

To elucidate the dynamics perspective of market competition, we draw on the real options framework. By the standard argument of real options, we can derive the upstream and downstream followers' value under symmetric information as follows:

Proposition 1 (Followers' value under symmetric information) *Under symmetric information, value functions of the upstream and downsream followers challenging type i technology for $i \in \{g, b\}$ are*

$$U_F^i(x) = \Big[\frac{(1-p_i)\beta\pi_D^F X_F^i}{r-\mu} - c_F\Big]\Big(\frac{x}{X_F^i}\Big)^\alpha, \tag{2.3}$$

$$D_F^i(x) = \frac{(1-p_i)(1-\beta)\pi_D^F X_F^i}{r-\mu}\Big(\frac{x}{X_F^i}\Big)^\alpha \tag{2.4}$$

where the upstream follower's investment trigger is

$$X_F^i = \frac{\alpha(r-\mu)c_F}{(\alpha-1)(1-p_i)\beta\pi_D^F}. \tag{2.5}$$

PROOF See the appendix of Jeon (2018).

This implies that the upstream follower invests at a cost c_F and makes an offer of licensing to the downstream follower when the demand shock reaches the level of X_F^i. The offer is accepted immediately because the downstream follower can raise revenue without any costs. It is natural that $X_F^b < X_F^g$ holds; given a higher p, the follower delays the investment until the demand grows enough to compensate the risk of gaining nothing in spite of the incurred costs. That is, the monopoly of the patented technology is expected to last longer for a higher p.

Given these arguments, now we can proceed to the upstream leader's investment decision and the license contract with the downstream leader. The leaders' bargaining differs from that of the followers because they have outside options. When disagreed, the upstream leader can make a license contract with the downstream follower, while the downstream leader can wait until the upstream follower challenges the leader and license the follower's technology.[3] The difference, however, is that the upstream leader can still be a leader in the industry when the bargaining breaks down, whereas the downstream leader becomes a follower in that case. The outcome of the bargaining is as follows:

Proposition 2 (Leaders' sharing rule under symmetric information) *Given demand shock X at the timing of bargaining, the downstream leader pays the following royalties per unit for type $i \in \{g, b\}$ technology:*

$$\theta_i(X) = \beta\Big[1 + (1-\beta)\Big\{1 - \frac{\Pi_i^F(X)}{\Pi_i^L(X;X)}\Big\}\Big] \tag{2.6}$$

leader and follower have that of $1-\beta$.

[3] We implicitly assume that there is no difference between the downstream leader and follower in terms of their production facilities; both downstream firms can make products based on both upstream firms' technologies. This is an out-of-equilibrium path, and there should be no confusion regarding the designation of the downstream firms as the leader and follower.

where

$$\Pi_i^L(x;X) := \frac{\pi_M X}{r-\mu}\Big(\frac{x}{X}\Big)^\alpha - \frac{(1-p_i)(\pi_M - \pi_D^L)X_F^i}{r-\mu}\Big(\frac{x}{X_F^i}\Big)^\alpha, \tag{2.7}$$

$$\Pi_i^F(x) := \frac{(1-p_i)\pi_D^F X_F^i}{r-\mu}\Big(\frac{x}{X_F^i}\Big)^\alpha \tag{2.8}$$

denote the expected profits of the leader and follower groups for current demand shock x, respectively.

PROOF See the appendix of Jeon (2018).

It is straightforward to show the following results regarding the sharing rule:

Corollary 1 *The per-unit royalties for the leader's technology decrease with the demand shock at which the bargaining is triggered, while the gap between the royalties of type g and type b technologies increases with the bargaining threshold:*

$$\frac{\partial\theta_i(X)}{\partial X} < 0, \tag{2.9}$$

$$\frac{\partial\{\theta_g(X) - \theta_b(X)\}}{\partial X} > 0. \tag{2.10}$$

PROOF See the appendix of Jeon (2018).

Given the rival's challenge, the effective maturity of the leader's patent decreases as the beginning of its use is delayed, and thus, (2.9) holds. The relative difference between the effective maturities of type g and type b technologies, however, increases as the technologies' uses are postponed, and therefore, (2.10) holds.

Recall that before the investment, the upstream leader only knows the distribution of the technology's type. Thus, the upstream leader's optimization problem under symmetric information is described as follows:

$$\sup_X \; q\theta_g(X)\Pi_g^L(x;X) + (1-q)\theta_b(X)\Pi_b^L(x;X) - c_L\Big(\frac{x}{X}\Big)^\alpha \tag{2.11}$$

By solving this problem, we can obtain the value functions of the upstream and downstream leaders as follows:

Proposition 3 (Leaders' value under symmetric information) *Under symmetric information, the upstream and downstream leaders' pre-investment values are*

$$U_L(x) = qU_L^g(x) + (1-q)U_L^b(x), \tag{2.12}$$

$$D_L(x) = qD_L^g(x) + (1-q)D_L^b(x) \tag{2.13}$$

where

$$U_L^i(x) = \theta_i(X_L)\Pi_i^L(x;X_L) - c_L\Big(\frac{x}{X_L}\Big)^\alpha, \tag{2.14}$$

$$D_L^i(x) = (1-\theta_i(X_L))\Pi_i^L(x;X_L) \tag{2.15}$$

and the upstream leader's investment trigger X_L is implicitly determined by solving (2.11) *with the sharing rule of* (2.6).

It follows the same argument of Proposition 1 to derive these results.

The followers' value functions before the leader's investment are the expected values of those from Proposition 1:

$$U_F(x) = qU_F^g(x) + (1-q)U_F^b(x), \tag{2.16}$$

$$D_F(x) = qD_F^g(x) + (1-q)D_F^b(x) \tag{2.17}$$

and we can evaluate total firm value in the market as follows:

$$T(x) = L(x) + F(x) \tag{2.18}$$

where $L(x) = U_L(x) + D_L(x)$ and $F(x) = U_F(x) + D_F(x)$ denote the value of the leader and follower groups, respectively.

2.3 Main model: asymmetric information

Suppose that other parties besides the upstream leader are not able to identify the true novelty of the upstream leader's technology. Given this uncertainty, the technology's user will pay royalties based on its expected value. In other words, the owner of type g technology raises less revenue than it should due to incomplete information. Thus, type g leader is willing to reveal its private information about the invention so that its user can identify the technology's true value and pay a fair amount royalty. For instance, innovators can put the timing of publication of patent applications forward. After AIPA, every patent application in the U.S. is published within 18 months from the earliest filing date, even if the patent is not granted yet; it can be published even earlier than that at the applicant's request. However, the applicant can also request not to publish it by certifying that it has not and will not be the subject of an application filed in another country.[4] They can also disclose their private information via other mechanisms; publications via private firms such as IP.com and Research Disclosure, Inc., industry reports, trade bulletins, technical journals, and postings on their websites (e.g., Hegde and Luo (2017), Baker and Mezzetti (2005)). In this sense, it is reasonable to suppose that the innovator can choose the extent of information disclosure at its will.

The disclosed information, however, is inevitably diffused to its rival as well, and accelerates the challenge by saving the rival's investment costs. Namely, the upstream follower's investment costs decrease to $(1-\gamma)c_F$ where $\gamma \in [0,1]$ denotes the degree of the leader's information disclosure. Suppose for the moment that information disclosure successfully reveals the technology's true type. Then, following the argument from Proposition 1, the followers' values under asymmetric information are derived as follows:

Proposition 4 (Followers' value under asymmetric information) *Under asymmetric information, value functions of the upstream and downstream firms challenging type i technology*

[4] See 35 U.S. Code §122 for the stipulation.

in the presence of information disclosure γ_i for $i \in \{g, b\}$ are

$$\bar{U}_F^i(x) = \Big[\frac{(1-p_i)\beta\pi_D^F\bar{X}_F^i(\gamma_i)}{r-\mu} - c_F\Big]\Big(\frac{x}{\bar{X}_F^i(\gamma_i)}\Big)^{\alpha}, \tag{2.19}$$

$$\bar{D}_F^i(x) = \frac{(1-p_i)(1-\beta)\pi_D^F\bar{X}_F^i(\gamma_i)}{r-\mu}\Big(\frac{x}{\bar{X}_F^i(\gamma_i)}\Big)^{\alpha} \tag{2.20}$$

where the upstream follower's investment trigger is

$$\bar{X}_F^i(\gamma) = \frac{\alpha(r-\mu)(1-\gamma)c_F}{(\alpha-1)(1-p_i)\beta\pi_D^F}. \tag{2.21}$$

It is obvious that $\bar{X}_F^i(0)$ is equal to X_F^i and that $\bar{X}_F^i(\gamma)$ decreases in γ. The latter implies that the signaling of technology's quality via information disclosure comes at the cost of a competitor's earlier challenge. The relative costs of the rival's earlier challenge, however, depend on the technology's novelty, and this enables the owner of type g technology to separate itself from type b innovator by disclosing private information.

Now let us proceed to the leader's decision of investment timing and information disclosure. Suppose the upstream leader invested at the trigger X and observed its technology's type. Given higher royalties for type g technology, the owner of type b technology has an incentive to mimic type g innovator's behavior so that it deceives the downstream firm and receives higher royalties than it should. Even though the downstream firm cannot identify the technology's true novelty directly, it can observe the disclosed information. If the upstream leader with type i technology discloses a fraction γ of its private information and receives the per-unit royalties θ based on the perceived type, we can evaluate the firm value as follows:

$$\bar{U}_L^i(X;\gamma,\theta) = \frac{\theta}{r-\mu}\Big[\pi_M X - (1-p_i)(\pi_M - \pi_D^L)\bar{X}_F^i(\gamma)\Big(\frac{X}{\bar{X}_F^i(\gamma)}\Big)^{\alpha}\Big], \qquad \forall i \in \{g, b\}. \tag{2.22}$$

Note that even though the royalties are based on the perceived type, the probability of winning the patent trial depends on the technology's true novelty. Thus, the cost of information disclosure depends on the innovator's type, and the following result holds:

Proposition 5 (Single-crossing condition) *The innovator with type g technology finds it less costly to disclose its private information than the owner of type b technology does such that the single-crossing condition holds:*

$$\frac{\partial}{\partial p_i}\Big(\frac{\partial\theta}{\partial\gamma}\frac{\gamma}{\theta}\Big) < 0. \tag{2.23}$$

PROOF See the appendix of Jeon (2018).

For this reason, type g leader can reveal its private information and separate itself from type b innovator, receiving a fair royalty from the downstream leader.

When information disclosure γ_i for type i technology reveals the technology's true type, the outcome of royalties bargaining is similar to the one from Proposition 2, except that the follower's challenge is accelerated by the disclosed information:

Proposition 6 (Leaders' bargaining under asymmetric information) *Given demand shock X at the timing of bargaining and information disclosure γ_i, the downstream leader pays the following royalties per unit for type $i \in \{g, b\}$ technology:*

$$\bar{\theta}_i(X, \gamma_i) = \beta\Big[1 + (1-\beta)\Big\{1 - \frac{\bar{\Pi}_i^F(X, \gamma_i)}{\bar{\Pi}_i^L(X, \gamma_i; X)}\Big\}\Big] \tag{2.24}$$

where

$$\bar{\Pi}_i^L(x, \gamma_i; X) := \frac{\pi_M X}{r-\mu}\Big(\frac{x}{X}\Big)^{\alpha} - \frac{(1-p_i)(\pi_M - \pi_D^L)\bar{X}_F^i(\gamma_i)}{r-\mu}\Big(\frac{x}{\bar{X}_F^i(\gamma_i)}\Big)^{\alpha}, \tag{2.25}$$

$$\bar{\Pi}_i^F(x, \gamma_i) := \frac{(1-p_i)\pi_D^F \bar{X}_F^i(\gamma_i)}{r-\mu}\Big(\frac{x}{\bar{X}_F^i(\gamma_i)}\Big)^{\alpha} \tag{2.26}$$

denote the expected profits of the leader and follower groups for current demand shock x and information disclosure γ_i, respectively.

In addition to Corollary 1, which holds under asymmetric information as well, the following results hold regarding the sharing rule and information disclosure:

Corollary 2 *The per-unit royalties for the leader's technology decrease with the degree of information disclosure, while the gap between the royalties of type g and type b technologies increases with the information disclosure:*

$$\frac{\partial \bar{\theta}_i(X, \gamma)}{\partial \gamma} < 0, \tag{2.27}$$

$$\frac{\partial\{\bar{\theta}_g(X, \gamma) - \bar{\theta}_b(X, \gamma)\}}{\partial \gamma} > 0. \tag{2.28}$$

PROOF See the appendix of Jeon (2018).

As the leader reveals information, the timing of the rival's challenge is put forward, which shortens the effective maturity of the leader's patent. Thus, (2.27) holds. The relative difference between the effective maturities of type g and type b technologies, however, rather increases as the rival's challenge is accelerated by information disclosure, and this leads to (2.28). In other words, type b owner's incentive to mimic type g's behavior becomes even stronger as information is disclosed, which makes type g's separation more costly.

Given this sharing rule, the owner of type b technology gives up mimicking type g innovator when the following holds:

$$\bar{\theta}_b(X, 0)\bar{\Pi}_b^L(X, 0; X) \geq \bar{\theta}_g(X, \gamma)\bar{\Pi}_b^L(X, \gamma; X). \tag{2.29}$$

The left-hand side of (2.29) is type b innovator's value when it does not disclose any private information, leaving the follower's investment timing same as that under symmetric information, and receives fair royalties. The right-hand side corresponds to type b innovator's value when it discloses γ of its private information, which accelerates the rival's challenge, and is perceived as type g, receiving higher royalties than it should. The binding case of (2.29) yields $\bar{\gamma}$, over which type b leader gives up mimicking type g because of the burden of the rival's earlier challenge. In other words, type b leader chooses to disclose its private information and pretends to be of type g when type g innovator discloses less than $\bar{\gamma}$. Note that the degree of information disclosure $\bar{\gamma}$ depends on the investment trigger X. As will be shown shortly, they are determined simultaneously and interact with each other.

Similarly, type g leader's incentive compatibility condition is as follows:

$$\bar{\theta}_g(X,\gamma)\bar{\Pi}_g^L(X,\gamma;X) \geq \bar{\theta}_b(X,0)\bar{\Pi}_g^L(X,0;X). \tag{2.30}$$

We can derive $\bar{\gamma}_{\max}$, over which type g gives up separating itself from type b from the binding case of (2.30). It is obvious that the separating equilibrium exists when $\bar{\gamma} \leq \bar{\gamma}_{\max}$. After the realization of technology's type, the upstream leader discloses its private information by the following rule:

Proposition 7 (Information disclosure) *The owner of type g technology discloses a fraction $\bar{\gamma}$ of its private information derived from* (2.29)*, whereas type b innovator reveals nothing:*

$$\gamma_g = \bar{\gamma}, \quad \gamma_b = 0 \tag{2.31}$$

provided $\bar{\gamma} \leq \bar{\gamma}_{\max}$ holds.

This result amounts to the upstream follower's investment triggers of $\bar{X}_F^g(\bar{\gamma})$ and $\bar{X}_F^b(0)(= X_F^b)$ and the royalties of $\bar{\theta}_g(X,\bar{\gamma})$ and $\bar{\theta}_b(X,0)$ for each type of technology, respectively.

Given these arguments, we can formulate the upstream leader's optimization problem under asymmetric information as follows:

$$\sup_{X,\gamma} \; q\bar{\theta}_g(X,\gamma)\bar{\Pi}_g^L(x,\gamma;X) + (1-q)\bar{\theta}_b(X,0)\bar{\Pi}_b^L(x,0;X) - c_L\left(\frac{x}{X}\right)^{\alpha} \tag{2.32}$$

subject to (2.29) and (2.30). The upstream leader choose the investment trigger X and the degree of information disclosure for type g technology γ without knowing the technology's quality. After the investment, which incurs a cost of c_L, type g technology is obtained with probability q and the innovator discloses a fraction γ of private information to show that the technology is worth royalties of $\bar{\theta}_g(X,\gamma)$, in spite of the costs of earlier challenge by the rival. With probability $1-q$, however, the technology is found to be of type b and the firm does not disclose any private information, receiving royalties of $\bar{\theta}_b(X,0)$.

In the separating equilibrium, as described in Proposition 7, the owner of more valuable technology discloses its private information about the invention, while the inventor with less valuable technology reveals nothing. This is consistent with the results from theoretical analyses by Gick (2008) and Anton and Yao (2002, 2008). The former investigates innovators' signaling via patent disclosure in the presence of upstream competition, and shows that more advanced firms disclose in spite of the costs, while less advanced firms disclose nothing. The paper, however, did not provide a detailed description of how exactly the disclosure incurs a cost to them. In contrast, we illustrate the cost of information disclosure by incorporating the follower's challenge against the leader's monopolistic position in the market. The latter, Anton and Yao (2002, 2008) studied the sale of ideas in the presence of downstream competition, and showed that the seller with more valuable idea reveals more private information to separate itself from the one with less valuable idea. Their works, however, drew on a static model, whereas we elucidate the dynamics perspective of technology market and analyze how the decisions of investment timing and information disclosure interact with each other, as will be shown in the following section.

This result is also in line with empirical evidence from Graham and Hegde (2015). As mentioned earlier, patent applicants who have not and will not apply for foreign patents can request confidentiality until the patent is granted. They investigate patent applicants' decision about disclosure before and after the enactment of AIPA and find that a large proportion of applicants without a parallel foreign filling, that is, those who could have opted out of the 18-month publication, actually chose pre-grant disclosure over pre-grant secrecy.[5] Namely, a large number of innovators have disclosed their private information on purpose. The authors suggest that patent disclosure benefits inventors, such as by credibly convincing their licensees, competitors, and investors. Mihm et al. (2015) also claims that a patenting firm discloses its research activities and gives signals about the quality of solutions resulting from its R&D efforts. Our model provides a theoretical framework to clarify the mechanism of innovators' signaling to licensees and competitors via information disclosure.

To sum up, we can calculate the leaders' value functions under asymmetric information as follows:

Proposition 8 (Leaders' value under asymmetric information) *Under asymmetric information, the upstream and downstream leaders' pre-investment values are*

$$\bar{U}_L(x) = q\bar{U}_L^g(x) + (1-q)\bar{U}_L^b(x), \tag{2.33}$$
$$\bar{D}_L(x) = q\bar{D}_L^g(x) + (1-q)\bar{D}_L^b(x) \tag{2.34}$$

where

$$\bar{U}_L^i(x) = \bar{\theta}_i(\bar{X}_L,\gamma_i)\bar{\Pi}_i^L(x,\gamma_i;\bar{X}_L) - c_L\left(\frac{x}{\bar{X}_L}\right)^\alpha, \tag{2.35}$$
$$\bar{D}_L^i(x) = (1-\bar{\theta}_i(\bar{X}_L,\gamma_i))\bar{\Pi}_i^L(x,\gamma_i;\bar{X}_L) \tag{2.36}$$

and the upstream leader's investment trigger $\bar{X}_L$ and information disclosure γ_i are implicitly determined by solving (2.32) *subject to* (2.29) *and* (2.30) *with the sharing rule of* (2.24).

The followers' value functions before the leader's investment are expected values of those from Proposition 4:

$$\bar{U}_F(x) = q\bar{U}_F^g(x) + (1-q)\bar{U}_F^b(x), \tag{2.37}$$
$$\bar{D}_F(x) = q\bar{D}_F^g(x) + (1-q)\bar{D}_F^b(x) \tag{2.38}$$

which amounts to the following total firm value under asymmetric information:

$$\bar{T}(x) = \bar{L}(x) + \bar{F}(x) \tag{2.39}$$

[5] They find that conditional on choosing against foreign protection (about 50% of the applications), about 85% of inventors chose pre-grant disclosure.

where $\bar{L}(x) = \bar{U}_L(x) + \bar{D}_L(x)$ and $\bar{F}(x) = \bar{U}_F(x) + \bar{D}_F(x)$ denote the value of the leader and follower groups under asymmetric information, respectively.

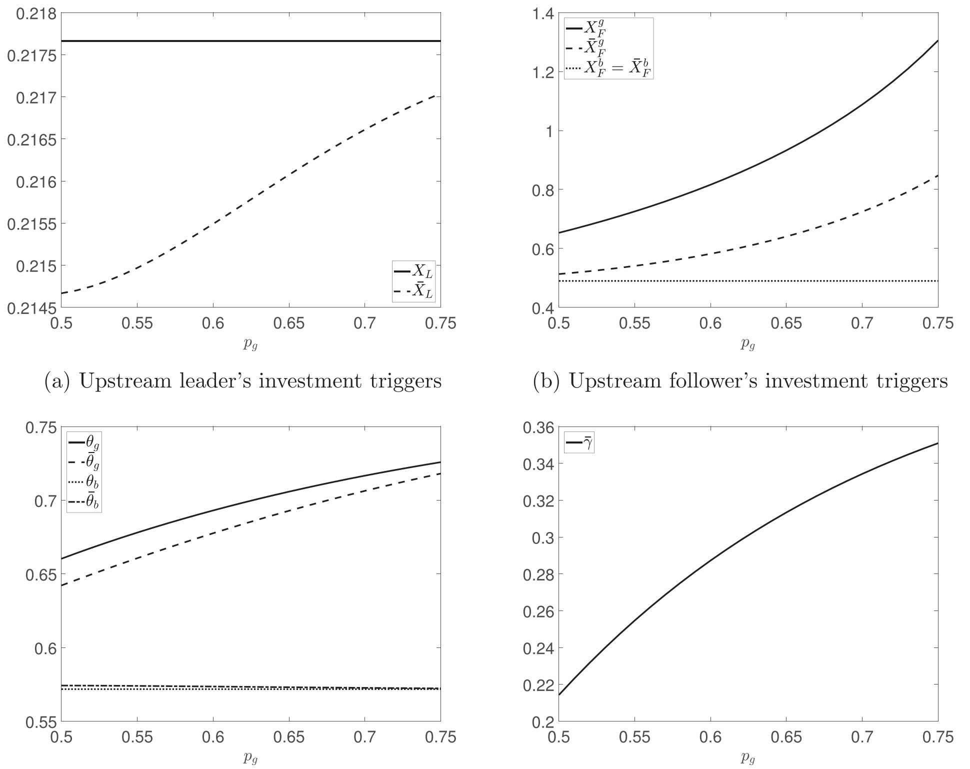
3 Comparative statics and discussion

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

$$r = 0.05, \quad \mu = 0.02, \quad \sigma = 0.2, \quad p_g = 2/3, \quad p_b = 1/3, \quad \beta = 0.5,$$
$$c_L = c_F = 2, \qquad \pi_M = \pi_D = 1, \quad \pi_D^F = \pi_D, \quad x_0 = 0.1.$$

3.1 Asymmetry in technology's novelty

First, we examine how the asymmetry in the novelty of the leader's technology affects the investment timing of the upstream leader and follower and the degree of information disclosure. We fix $p_b = 1/3$ and let p_g vary from 1/2 to 3/4.



(a) Upstream leader's investment triggers

(b) Upstream follower's investment triggers

(c) Royalties

(d) Type g's information disclosure

Figure 1: Comparative statics with respect to the asymmetry in technology's novelty

We can observe the following result from Panel (d) of Figure 1:

Observation 1 *The more valuable the technology is, the more its owner discloses private information about it. That is, $\bar{\gamma}$ strictly increases in p_g.*

This is because type b innovator has stronger incentives to pretend to have type g technology when p_g is much higher than p_b. Note that the royalties for type g strictly increase in p_g (Panel (c)). This result is consistent with theoretical analysis by Anton and Yao (2002, 2008) and empirical evidence from Graham and Hegde (2015). The former investigates the sale of ideas in the presence of downstream competition and shows that the amount of disclosure increases with the ideas' value. The latter shows that applicants of the patents with more values are more likely to choose pre-grant disclosure over pre-grant secrecy.[6]

Meanwhile, this result is in contrast to the argument from Anton and Yao (2003, 2004). They examine duopoly competition with asymmetric information on the cost structure and show that inventors with better technology discloses less knowledge. The difference in the results comes from the incentive to disclose in their models. They suppose that the leader transfers knowledge to the follower on purpose to affect the follower's capacity decision. In our model, the upstream leader discloses its private information so that the downstream leader can pay fair royalties, and it is inevitably diffused to the follower.

It is obvious that the disclosed information affects the investment timing of both the upstream leader and follower, and Panels (a) and (b) of Figure 1 show the following result:

Observation 2 *Under asymmetric information, not only the upstream follower challenging type g technology, the beneficiary of information disclosure, but also the upstream leader invests earlier than they would have under symmetric information. That is, $\bar{X}_F^g$ and $\bar{X}_L$ are lower than X_F^g and X_L, respectively.*

Given information disclosure $\bar{\delta}$, it is obvious that the follower challenging type g technology invests earlier; it can save the investment costs for duplicative R&D by referring to the disclosed information. Note that not only X_F^g and $\bar{X}_F^g$ but also the gap between them strictly increases in p_g due to the increase of $\bar{\gamma}$ (Panel (d)).

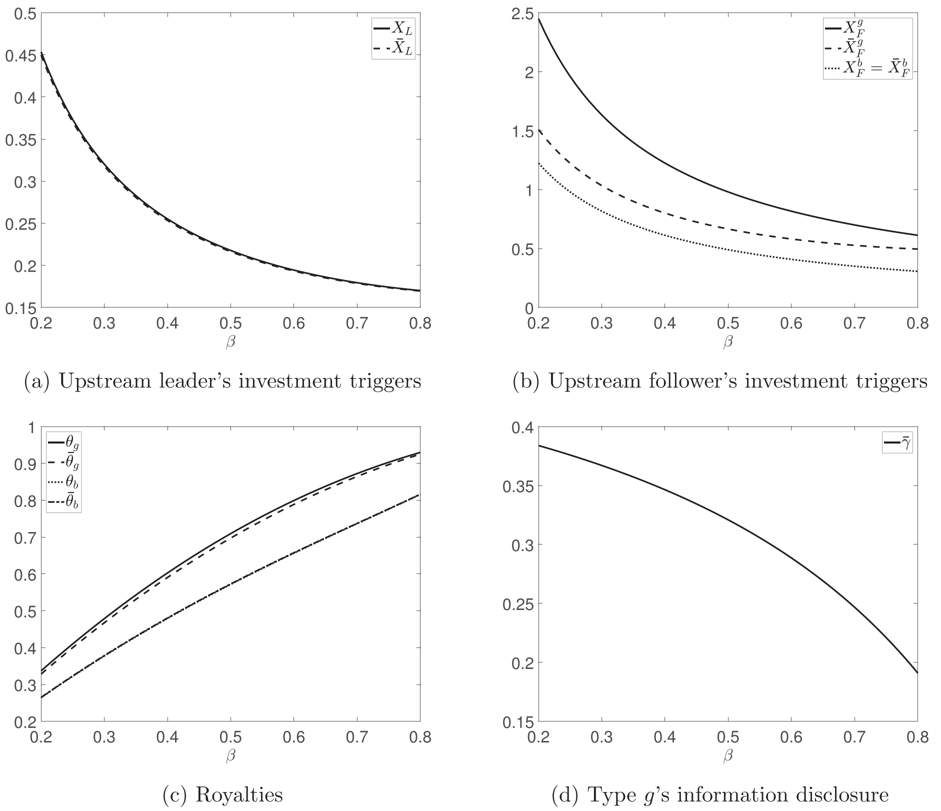
The leader's overinvestment in R&D under asymmetric information can be construed as follows. The leader group has to raise enough revenue before the follower group's challenge, of which timing is put forward due to the revealed information. From the perspective of optimization problems in (2.11) and (2.32), $\bar{\Pi}_g^L(x, \gamma; X)$ is lower than $\Pi_g^L(x; X)$ given demand shock X, and thus, the leader has an incentive to choose $\bar{X}_L$ lower than X_L. Furthermore, earlier investment raises the royalties $\bar{\theta}_g(X, \gamma)$ and $\bar{\theta}_b(X, 0)$ in (2.32) via multiple channels: first, a lower investment threshold directly raises them by (2.9) from Corollary 1, and second, a lower investment trigger reduces $\bar{\delta}$, the minimum amount of information disclosure necessary for the separation, by disincentivizing type b owner to mimic type g, which can be inferred from (2.10) of Corollary 1, and lastly, a lower level of disclosure raises $\bar{\theta}_g(X, \gamma)$ by (2.27) from Corollary 2.

[6] They use three different measures to evaluate the value of patents: the number of claims, the amount of maintenance fees, and the number of citations. The result was robust in that all three measures pointed in the same direction.

Earlier investment in R&D in the presence of information disclosure is in contrast with the conventional wisdom that the need to disclose complementary information will retard innovation. Aoki and Spiegel (2009) examine the implications of pre-grant publication, taking cumulative innovation into account, and claim that it will eventually lead to fewer inventions. Gans et al. (2008) point out that uncertainty from the process of patent grants impedes the transfer of technology, showing that the hazard rate for achieving a cooperative licensing significantly increases after patents are granted. We analyze the interaction of the decisions of information disclosure and investment timing, taking the dynamics perspective into account, and show that innovators' voluntary disclosure under asymmetric information accelerates the innovators' R&D investment.

3.2 Firms' bargaining power

Now we examine how the firms' bargaining power changes the arguments of our model. We let β, the bargaining power of upstream firms, vary from 0.2 to 0.8.



(a) Upstream leader's investment triggers

(b) Upstream follower's investment triggers

(c) Royalties

(d) Type g's information disclosure

Figure 2: Comparative statics with respect to the bargaining power

We can see the following result from Panels (b) and (d) of Figure 2:

Observation 3 *The less bargaining power the innovator has, the more it discloses its private information. That is, the amount of information revealed by type g leader strictly decreases in* β*, which leads to a decrease in the gap between* X_F^g *and* $\bar{X}_F^g$

When β is low, the royalties for innovators will be low, which makes type b innovators more eager to pretend to be of type g. Thus, the owner of type g technology has to reveal more private information to separate itself from type b owner. This finding is also consistent with Graham and Hegde (2015) in that their result is more significant for small innovators, whose bargaining power is expected to be low.

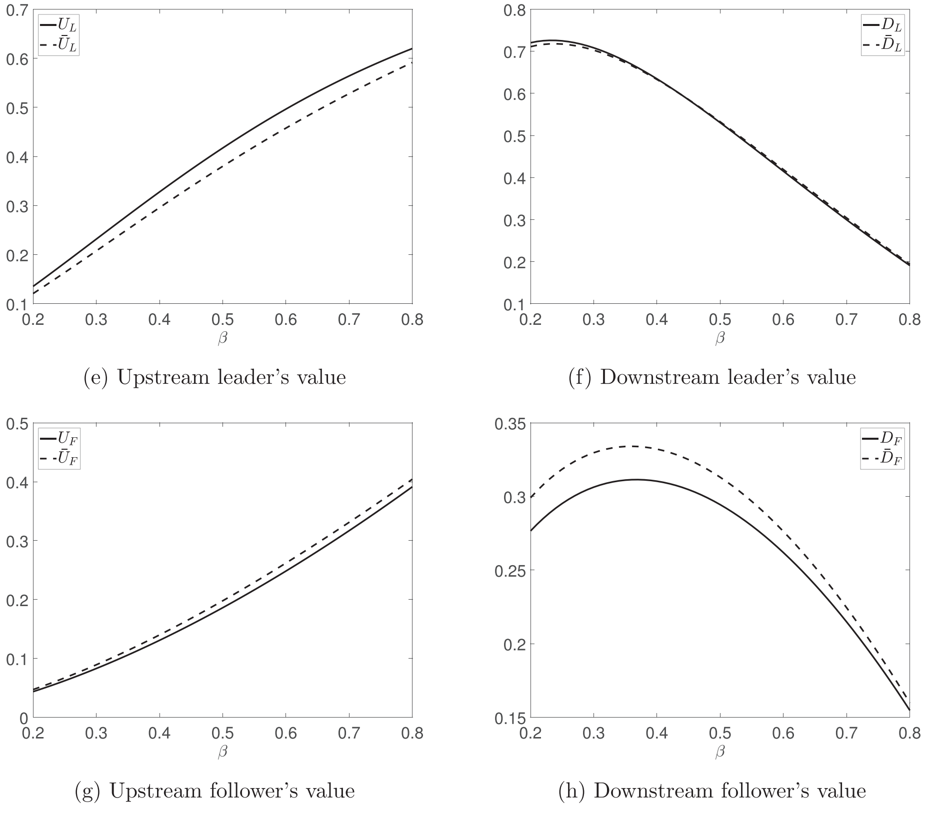
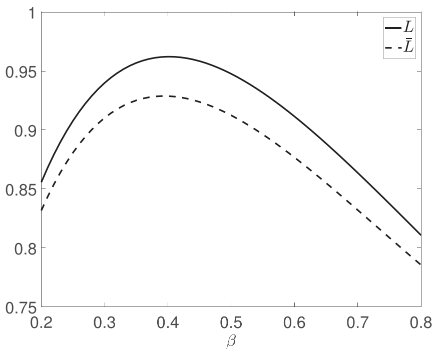


Figure 2: Comparative statics with respect to the bargaining power

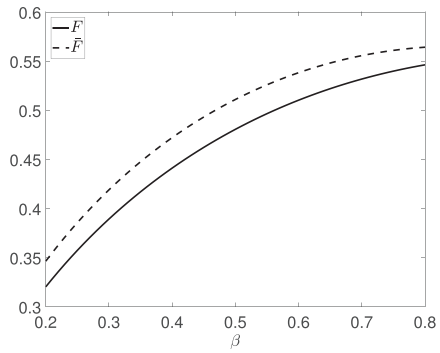
Regarding the firms' values, we can observe the following result from from Panels (e) through (h) of Figure 2:

Observation 4 *The upstream firms' value strictly increases in* β*, whereas the downstream firms' values are not monotone with respect to their bargaining power,* $1-\beta$*. The total value of the firms in the market is concave with respect to* β*.*

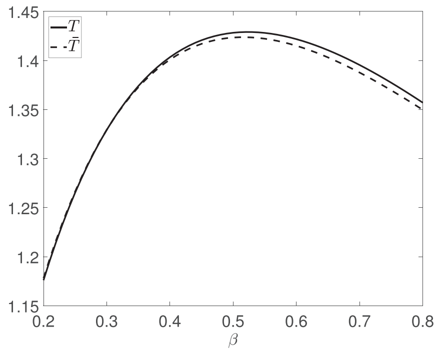
When β is significantly low, the invention of technology, from which the downstream firms make revenue, is delayed significantly (Panels (a) and (b)). Thus, their expected values do not increase despite the low royalties for low β. This leads to the result in Panel (k): the concavity between β and the total value of the firms in the market. This implies that social welfare worsens when either a licensor or a licensee has an overwhelming position in the market. This result can be read from the context of Shapiro (2008), which notes that excessive rewards provided to patent holders can rather stifle innovation. Jeon and Nishihara (2017) investigate the bilateral hold-up problem in a vertically separated market and also find that overcompensation for innovators worsens social welfare by delaying the technology licensing. Though we do not explicitly consider the government's policies, it is natural to suppose that bargaining power of the firms in technology market is directly linked to the government's policies on intellectual property rights. In this sense, our model suggests that the government's policies should keep a balance between the inventors of technologies and their users.



(i) Leaders' value



(j) Followers' value



(k) Total firm value

Figure 2: Comparative statics with respect to the bargaining power

Furthermore, we can observe the following result from Panel (k) of Figure 2:

Observation 5 *When β is significantly low, the total value of the firms in the market under asymmetric information is higher than that under symmetric information.*

It is of special interest that social welfare can improve due to information asymmetry. This is also directly associated with Panel (d), the extent of information disclosure under asymmetric information. As noted by Observation 3, type g innovator reveals more information when its bargaining power is low. In other words, more investment costs are saved in the society as a whole when the upstream firm has less bargaining power. Though the leaders suffer losses from the rival's earlier challenge, the followers' benefit can dominate them. This finding supports the requirement of pre-grant publication from the perspective of R&D spillover. National surveys in the U.S. and Japan by Cohen et al. (2002) show that the diffusion-oriented patent system in Japan leads to greater R&D spillover at the cost of less appropriability for innovators. Our model suggests that the gains from the diffusion of knowledge are greater and can even dominate the patentees' losses when innovators have low bargaining power.

4 Conclusion

In this paper, we examined a license contract in a vertically separated market in the presence of a rival's challenge and information asymmetry regarding technologies' values. The innovator with more valuable technology voluntarily discloses its private information about the invention to separate itself from the one with less valuable technology so that it can raise a fair royalty payment. The disclosed information, however, is diffused to the follower as well, and leads to an earlier challenge by saving the rival's investment costs for duplicative R&D. The inventor's voluntary disclosure of its private information is consistent with empirical evidence of U.S. inventors' strategies after AIPA; a choice of pre-grant publication over pre-grant secrecy. The amount of disclosed information increases with the asymmetry of a technology's novelty and decreases with the innovator's bargaining power. We also showed that the timing of the leader's innovation moves forward under asymmetric information, which is in contrast to the conventional wisdom that information disclosure will stifle innovation. In spite of the leader's losses from the rival's earlier challenge, the total value of the firms in the market may increase under asymmetric information by avoiding investment in duplicative R&D, especially when the innovator's bargaining power is low.

References

Anton, J. and Yao, D. (2002), 'The sale of ideas: strategic disclosure, property rights, and contracting', *Review of Economic Studies* **69**, 513–531.

Anton, J. and Yao, D. (2003), 'Patents, invalidity, and the strategic transmission of enabling information', *Journal of Economics and Management Strategy* **12**, 151–178.

Anton, J. and Yao, D. (2004), 'Little patents and big secrets: managing intellectual property', *RAND Journal of Economics* **35**, 1–22.

Anton, J. and Yao, D. (2008), 'Attracting skeptical buyers: Negotiating for intellectual property rights', *International Economic Review* **49**, 319–348.

Aoki, R. and Spiegel, Y. (2009), 'Pre-grant patent publication and cumulative innovation', *International Journal of Industrial Organization* **27**, 333–345.

Baker, S. and Mezzetti, C. (2005), 'Disclosure as a strategy in the patent race', *Journal of Law and Economics* **48**, 173–194.

Cohen, W., Goto, A., Nagata, A., Nelson, R. and Walsh, J. (2002), 'R&D spillovers, patents and the incentives to innovate in Japan and the United States', *Research Policy* **31**, 1349–1367.

Gans, J., Hsu, D. and Stern, S. (2008), 'The impact of uncertain intellectual property rights on the market for ideas: Evidence from patent grant delays', *Management Science* **54**, 982–997.

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

Graham, S. and Hegde, D. (2015), 'Disclosing patents' secrets', *Science* **347**, 236–237.

Hegde, D. and Luo, H. (2017), 'Patent publication and the market for ideas', *Management Science* .

Jeon, H. (2018), Licensing and information disclosure under asymmetric information. Working paper.

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

Lemley, M. and Shapiro, C. (2005), 'Probabilistic patents', *Journal of Economic Perspectives* **19**, 75–98.

Levin, R., Klevorick, A. and Nelson, R. (1987), 'Appropriating the returns from industrial R&D', *Brookings Papers on Economic Activity* **1987**, 783–831.

Mihm, J., Stin, F. and Wang, T. (2015), 'On the effectiveness of patenting strategies in innovation races', *Management Science* **61**, 2662–2684.

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

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