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On optimal forward patent protection in sequential innovation

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Abstract

On optimal forward patent protection in sequential innovation

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This paper analyze the effect of forward patent protection via information friction in sequential innovation. In the model interpreting a sequential innovation as a repeated patent race, I examine what level of patent protection is optimal depending on the value of the final innovation. When social value is concentrated on the final innovation, the government has incentive to balance investment between patent races, which gives an explanation on the optimal patent protection level. If the innovation's value is sufficiently large, competitions occur on the optiaml protection level and this continues to hold even when heterogeneity exists in cost structuer of two patent races. However, when the first patent's value is sufficient large, the government interference is unnecessary as the policy using information friction in this paper works by transferring investment on the second race to the investment on the first race.

keywords : sequential innovation, patent race, forward patent protection, information friction

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1 Introduction

Patent policy is deemed to be an important way to facilitate innovation via faster information spread. One aspect of patent policy supporting this goal is pre-grant publication. Ragusa (1992) points out that many industrialized countries have adopted pre-grant publication policy of 18 months. Countries with this policy reveal patent applications to the public after 18 months have passed since application regardless of whether or not they will be granted. This policy seems to have accomplished its goal. Johnson and Popp (2003) uses U.S. patent data from 1976 to 1996 to conclude knowledge spillover starts after publication, from which it anticipates American Inventor's Protection Act[1] would stimulate knowledge flow. Okada and Nagaoka (2020) demonstrates that earlier publication leads to earlier citation, meaning faster knowledge spreads, by comparing applicant non-self-citation patterns to domestic patents before and after the American Inventor's Protection Act.

Intuitively, pre-grant publication policy creates a trade-off between the first and the second innovation. Assume every patent has to be made public after 18 months from its application. If the patent office decides to extend this period, this would stimulate R&D investment to the first investment. The winner of the first innovation would have a higher chance of reaping profits out of the second one, making the overall expected profit from the first innovation bigger. However, this policy change may stifle the second innovation. All followers may fear the first innovator may succeed in developing the second innovation faster than they can. Therefore, to avoid spending too much money on duplicate research, all followers have incentives to spend less. Anticipating this, the leader may have less incentive to invest in the second innovation too. This lack of incentives to compete fiercely in the second race may make the advent of the second innovation late. Overall, the total effect of pre-grant publication on innovation is ambiguous. This effect is not restricted to pre-grant publication policy. Any information frictions caused during

[1] By this act, applications filed on or after November 29, 2000, are required to be revealed 18 months after their effective filing dates with a limited exception. For additional information, refer to Okada and Nagaoka (2020) which uses this act to empirically estimate the effect of pre-grant publication policy of 18 months.

the patent registration process would have the same effect. For instance, the government may have a lax enforcement of reproducibility requirement on patents, allowing firms to use it as leverage to protect their innovation. The goal of this paper is to capture this trade-off to derive lessons for designing a forward protection policy.

To address this goal, this paper constructs a two-stage patent race model based on Denicolò (2000). Denicolò (2000)'s model allows multiple firms to compete in two subsequent patent races and investigates effects of patent policies. I add information friction's effect on Denicolò (2000)'s model so that information friction makes followers less likely to innovate than the first innovator during the second innovation race. Following Denicolò (2000)'s model, a firm's investment determines its instantaneous probability of success which is linear in its investment. To protect the first innovator, the government can choose a constant to scale probability of success of all followers during the second race. This constant is related to degree of protection offered by the government by delaying knowledge spillover from patent publication. This paper focuses on how this information friction shapes optimal investment of firms and influences innovations.

This paper is related to several lines of research. Above all, this paper adds to the literature on pre-grant publication policy. Aoki and Prusa (1996) argues that pre-grant publication allows firms to coordinate, leading to fewer improvements compared to the system in which patents are revealed only after granted. Aoki and Spiegel (2009) shows that pre-grant publication may lower the numbers of innovations while it may have positive welfare effects on product market. This paper differs from the previous literature, as this paper is more focused on interpreting pre-grant publication policy as an information friction and how the government can utilize this policy to optimally allocate investment between each patent race.

This work also is related to the literature of patent race inspired by Loury (1979). In this paper's model, firms compete in patent races in the style of Loury (1979)'s model. Also, to emphasize the proposed trade-off caused by the policy, the intrinsic value of intermediate(the first) innovation is set to be 0 in the main analysis, which is analogous to multi-stage R&D competition modeled in Grossman and Shapiro (1987), Fudenberg et al. (1983), and Bloch and Markowitz (1996). In terms of the content, this work is most similar to Bloch and Markowitz (1996) and Lim (1998), as both focus on the optimal delay of the first(intermediate) innovation's knowledge to competitors. This paper's model departs from two papers as it models innovation competition differently and allows multiple firms to participate as in Denicolò (2000).

Finally, this paper is related to the literature on the optimal patent protection policy regarding cumulative innovation. Green and Scotchmer (1995) shows that when sequential innovations are considered, the first innovator should be strongly protected. This paper aims to derive the optimal level of forward protection when information friction is used to protect the first innovator. This paper follows Denicolò (2000) to model a cumulative innovation as a repeated Loury (1979) style patent race. The way this paper introduces information friction to Denicolò (2000)'s model is similar to Erkal (2005)'s approach. Erkal (2005) investigates how the first innovator should be protected from the second innovation if the first innovator can choose to patent or not. In Erkal (2005)'s model, opponents have a smaller chance of innovation compared to the first patent holder like in this paper. However, this paper departs from Erkal (2005)'s model as this paper more directly focuses on choosing the optimal level of protection and ignores the possibility of trade secret. Also, this paper aims to show that even without a patent infringement decision which forces followers to share their profit with the leader, firms sill have incentives to enter the patent races.

The rest of the paper is organized as the following. Chapter 2 describes the model. Chapter 3 characterizes the solution of the baseline model and finds the optimal government protection level. Chapter 4 introduces two extensions of the model. Finally, Chapter 5 concludes.

2 Model

2.1 Patent race

During each period of the entire patent races, all participating firms compete in the style of Loury (1979). At the beginning of each race, firm i chooses its investment level x_i and pays a lump-sum cost cx_i, where c represents the common cost of R&D for all periods, to become the innovator of patents whose statutory lives are both infinity. For tractability, I assume the instantaneous probability of innovation is also x_i if there is no government intervention. I assume the value of the second patent is exogenously given as a flow of rV and all firms share a common interest rate r, so that the size of the prize is V considering the discount. Therefore, the patent races are essentially the same as the Denicolò (2000)'s setup. Ignoring government intervention, a typical firm i chooses x_i that maximizes

$$\pi_i = \int_0^\infty e^{-(X_2+r)t} x_i V dt - cx_i = \frac{x_i V}{X_2 + r} - cx_i$$

at the beginning of the second race, where X_2 is aggregated level of investment of all firms.

As I analyze the effect in sequential innovation, I assume the second patent can be invented only after the first patent is invented. To focus on the policy's effect, I also assume that the value of the first patent is 0 as in multi-stage R&D race literature. Therefore, firms enter the first race only if its expected payoff from the second race is large enough. Thus, if the expected profit from the second race of the leader(first innovator) is π_L, any firm entering the first patent race faces the following profit function:

$$\pi_i' = \int_0^\infty e^{-(X_1+r)t} x_i' \pi_L dt - cx_i = \frac{x_i' \pi_L}{X_1 + r} - cx_i'$$

where x_i' is the investment of the firm i and X_1 is aggregated level of investment in the first race. The government intervention shapes innovation incentives by altering π_L. Intuitively, higher π_L will make firms vigorously compete in the first race. However, this also means competing firms(followers) in the second race have a lower chance of innovation, which will be explained later. Therefore, the overall investment in the second race decreases as the π_L becomes larger.

2.2 Patent policy

I assume the winner of the second race enjoys the entire prize of the second innovation even without any rights for the first patent. Additionally, I assume the winner of the first race immediately files a patent application after any discoveries and all firms simultaneously enter the second patent race for tractability. Also, let the patent race be open to any firm so any firm would enter the competition if it expects a positive return. Therefore, all firms expect zero profit if there is no protection.

The government now chooses $1 - t \in [0, 1]$, the degree of forward protection. In this model, this t is multiplied to the follower's probability of success x_i to capture the effect of protection. The profit function of a follower f which chooses x_f is

$$\pi_f = \frac{t x_f V}{x_L + t X_F + r} - c x_f$$

in the second patent race where x_L is the investment of the leader and X_F is the aggregated investment of the followers.

As previously mentioned, many countries make patent applications public 18 months after filed. This creates a time lag between creation of new knowledge and its dissemination. This lag gives more time for the leader to develop subsequent innovation, thereby reducing the probability of innovation of followers. In this interpretation, t captures how much the followers are lagging by the pre-grant publication policy. Thus, the smaller t is, the longer time it takes to disclose discoveries, which works as a protection for the first innovator.

Another way of interpreting t would be information friction generated by a lax patent regulation. Ideally, patent should bear enough information for its readers to understand and reproduce innovation described. However, firms may be able to patent their innovation without revealing full information to the public. For instance, Sim (2021) investigates mixing trade secret and patent to protect a complex innovation. As in the paper, if firms can mix trade secret and patent, all followers would have lower probability of success even if they spend the same amount of money. In this sense, t is related to how lax government is in requiring patents to be specific enough to reproduce innovation, which would be an implicit protection for the first innovator.

Finally, $1-t$ can be regarded as the probability of infringement although this interpretation is not related to information friction channels which are the motivations for this paper. When a new product infringes the first patent, followers can discard their invention and continue research rather than making an agreement to split the profit with the first patent holder. This situation may occur when bargaining costs are too expensive. Again, lower t implies stronger protection for forward patents making followers have a lower instantaneous probability of success even if they spend the same amount of money.

3 Main results

3.1 Characterization of the equilibrium

Before characterizing the equilibrium, I additionally add an assumption of V. V should be large enough to cover the expenses of firms. If not, no firm would enter the innovation race. Therefore, to ensure firms enter the competition, I derive a condition for at least a monopoly firm to invest. In the second race, the monopoly firm chooses its investment level x to maximize

$$\pi = \frac{xV}{x+r} - cx$$

whose FOC is

$$\frac{d\pi}{dx} = \frac{rV}{(x+r)^2} - c = 0$$

Solving this, $x^* = \sqrt{\frac{rV}{c}} - r$ and $\pi^* = \left(\sqrt{V} - \sqrt{rc}\right)^2$

Therefore, in the first race, the monopoly firm choose x' to maximize

$$\pi' = \frac{x'(\sqrt{V} - \sqrt{rc})^2}{x'+r} - cx'$$

Similarly, $x'^{*} = \sqrt{\frac{r}{c}}\left(\sqrt{V}-\sqrt{rc}\right) - r$ and $\pi' = \left(\sqrt{V}-2\sqrt{rc}\right)^2$. As $x'^{*} \geq 0$ should be satisfied, $\sqrt{V} \geq 2\sqrt{rc}$ is required. This assumption also makes $x^{*} \geq 0$. For the remaining parts of this chapter, this assumption is maintained. By choosing the degree of forward protection, the government can change the degree of competition and the level of investment during the second patent race.

The following proposition shows one side of the trade-off generated by the government's forward patent protection.

Proposition 1. ***(Characterization of the second patent race)*** *For given $t \in [0,1]$,*

- *the leader's investment:* $x_L = \begin{cases} \frac{tV}{c} - \frac{t^2V}{c} & \textit{when } t \geq \sqrt{\frac{rc}{V}} \\ \sqrt{\frac{rV}{c}} - r & \textit{otherwise} \end{cases}$

- *the aggregated followers' investment:* $X_F = \begin{cases} \frac{tV}{c} - \frac{r}{t} & \textit{when } t \geq \sqrt{\frac{rc}{V}} \\ 0 & \textit{otherwise} \end{cases}$

- *the leader's expected profit:* $\pi_L = \begin{cases} V(1-t)^2 & \textit{when } t \geq \sqrt{\frac{rc}{V}} \\ \left(\sqrt{V}-\sqrt{rc}\right)^2 & \textit{otherwise} \end{cases}$

- *the effective aggregated investment:* $x_L + tX_F = \begin{cases} \frac{tV}{c} - r & \textit{when } t \geq \sqrt{\frac{rc}{V}} \\ \sqrt{\frac{rV}{c}} - r & \textit{otherwise} \end{cases}$

Proof. The profits of the leader and a typical following firm are given as:

$$\pi_L = \frac{x_L V}{x_L + tX_F + r} - cx_L$$
$$\pi_F = \frac{tx_F V}{x_L + tX_F + r} - cx_F$$

where x_L and x_F are the leader's investment and a typical follower's investment respectively. Due to the free entry condition, $\pi_F = 0$. Thus, we have

$$\pi_F = \frac{tx_F V - cx_F(x_L + tX_F + r)}{x_L + tX_F + r} = 0$$

Therefore,

$$x_F(tV - c(x_L + tX_F + r)) = 0 \tag{1}$$

with $x_F > 0$ only if $tV - c(x_L + tX_F + r) = 0$. On the other hand, the first order condition of the leader can be used to pin down optimal investment of the leader.

$$\frac{d\pi_L}{dx_L} = \frac{V(tX_F + r)}{(x_L + tX_F + r)^2} - c = 0 \tag{2}$$

We can solve two equations simultaneously to derive the optimal investment levels of firms. From (2),

$$\begin{aligned}
& \frac{V(tX_F + r)}{(x_L + tX_F + r)^2} - c = 0 \\
\Leftrightarrow \quad & \frac{V(tX_F + r)}{c} = (x_L + tX_F + r)^2 \\
\Leftrightarrow \quad & \frac{V(tX_F + r)}{c} = \frac{t^2V^2}{c^2} \qquad \text{from (1)} \\
\Leftrightarrow \quad & X_F = \frac{tV}{c} - \frac{r}{t}
\end{aligned}$$

Thus, $X_F = \max\{0, \frac{tV}{c} - \frac{r}{t}\}$. In other words, as in Proposition (1),

$$X_F = \begin{cases} \frac{tV}{c} - \frac{r}{t} & \text{when } t \geq \sqrt{\frac{rc}{V}} \\ 0 & \text{otherwise} \end{cases}$$

By plugging in X_F to (2), we can calculate X_L, which is

$$x_L = \begin{cases} \frac{tV}{c} - \frac{t^2V}{c} & \text{when } t \geq \sqrt{\frac{rc}{V}} \\ \sqrt{\frac{rV}{c}} - r & \text{otherwise} \end{cases}$$

Straightforward calculation leads to the aggregated investment, $x_L + tX_F$. Finally, recall

$$\pi_L = \frac{x_L V}{x_L + tX_F + r} - cx_L$$

inserting x_L and $x_L + tX_F$ gives

$$\pi_L = \begin{cases} \frac{x_L V}{x_L + tX_F + r} - cx_L = \frac{(\frac{tV}{c} - \frac{t^2V}{c})V}{(\frac{tV}{c} - r) + r} - c(\frac{tV}{c} - \frac{t^2V}{c}) = V(1-t)^2 & \text{when } t \geq \sqrt{\frac{rc}{V}} \\ \frac{\sqrt{\frac{rV}{c}} - r}{(\sqrt{\frac{rV}{c}} - r) + r} - c(\sqrt{\frac{rV}{c}} - r) = \left(\sqrt{V} - \sqrt{rc}\right)^2 & \text{otherwise} \end{cases}$$

□

This proposition shows how the policy acts as an incentive for the first innovator. As the protection strengthens(smaller t), the expected profit for the leader monotonically increases until the monopoly is guaranteed. That is, the government stimulates the first innovation by making the second race more favorable to the first innovator.

As the degree of protection strengthens following firms have a lower incentive to invest, which makes the aggregated investment of followers a non-decreasing function of t. On the other hand, the effect of t on the leader's investment is ambiguous. If the threshold($\sqrt{\frac{rc}{V}}$) is sufficiently small, x_L increases until $t = \frac{1}{2}$ and decreases afterwards. Intuitively, when $t \leq \sqrt{\frac{rc}{V}}$, only the leader enters the second race as all competitors expect a low probability of becoming the second innovator. Thus, firms tend to spend less if t becomes low as it expects more monopolistic competition, which eventually allows the leader to spend less. On the other hand, when t becomes larger, there is less incentive for the leader to enter the competition since it becomes more indifferent to followers gaining zero expected profit from the second innovation. However, the aggregated investment monotonically decreases as the protection gets stronger.

Therefore, this shows one side of the trade-off generated by the policy. As the information friction strengthens, the aggregated investment during the second patent race decreases, thereby slowing down the development of the second innovation.

The following proposition characterizes the optimal investment of firms in the first race. Since the first patent is assumed to have no innate value, the firms only care about the expected profit from becoming the first innovator. That is, the prize of the first race is π_L.

Proposition 2. ***(Characterization of the first patent race)*** *For given* $t \in [0, 1]$,

- $X_1 = 0$ $\quad$ *if* $1 - \sqrt{\frac{rc}{V}} < t$
- $X_1 = \frac{V(1-t)^2}{c} - r$ $\quad$ *if* $\sqrt{\frac{rc}{V}} < t \leq 1 - \sqrt{\frac{rc}{V}}$
- $X_1 = \frac{(\sqrt{V}-\sqrt{rc})^2}{c} - r$ $\quad$ *if* $t \leq \sqrt{\frac{rc}{V}}$

Therefore, the aggregated investment in the first race(X_1) is a monotone decreasing function of t. Note that $\sqrt{\frac{rc}{V}} \leq 1 - \sqrt{\frac{rc}{V}}$ as $\sqrt{V} \geq 2\sqrt{rc}$.

Proof. For a typical firm i at the beginning of the first patent race, its expected profit is given as:

$$\pi_i = \frac{x_i \pi_L}{X_1 + r} - cx_i$$

where X_1 is the aggregated sum of investment in the first patent race. $\pi_L = \left(\sqrt{V} - \sqrt{rc}\right)^2$ for $t < \sqrt{\frac{rc}{V}}$ and $\pi_L = V(1-t)^2$ for $t \geq \sqrt{\frac{rc}{V}}$ by the proposition (1).

Due to the free entry assumption,

$$x_i(\pi_L - c(X_1 + r)) = 0$$

with $x_i > 0$ only if $(\pi_L - c(X_1 + r)) = 0$. If t is large enough, π_L may not be enough the cover the first patent race's cost. This corresponds to the case when $1 - \sqrt{\frac{rc}{V}} < t$. $\square$

This proposition shows the other side of the trade-off. As the protection becomes stronger, firms are more willing to invest in the first patent race, which expedites the first innovation. Therefore, the government spurs the first innovation at the cost of slowing down the second innovation. Next, the optimal level of government intervention to maximize social welfare is discussed.

3.2 Social welfare

The expected social welfare, considering only the private values of patents, can be defined as

$$W \equiv \frac{X_1}{X_1 + r}\left[0 + \frac{x_L + tX_F}{x_L + tX_F + r}V - cX_2\right] - cX_1$$

where X_1 and X_2 are the aggregated investment in each innovation race while x_L and X_F are the leader's and the follower's aggregated investment in the second race respectively. This definition is from Denicolò (2000) but I first ignored the possibility of social benefits from each innovation unlike Denicolò (2000) to emphasize assuming existence of the social benefits from innovations is crucial for welfare analysis.[2] As in Denicolò (2000), $\frac{X_1}{X_1+r}$ and $\frac{x_L+tX_F}{x_L+tX_F+r}$ can be interpreted as the adjusted probability of success. Note that the aggregated followers' investments is scaled by t only in the second probability terms due to the government intervention. The following computation shows social welfare function is 0 for any values of t without considering the social value of the patents.

- when $t > 1 - \sqrt{\frac{rc}{V}}$: as $X_1 = 0$,

$$W = \frac{0}{0+r}\left[0 + \frac{x_L + tX_F}{x_L + tX_F + r}V - cX_2\right] - c \cdot 0 = 0$$

- when $\sqrt{\frac{rc}{V}} < t \leq 1 - \sqrt{\frac{rc}{V}}$: plugging in both values,

$$W = \frac{\frac{V(1-t)^2}{c} - r}{(\frac{V(1-t)^2}{c} - r) + r}\left(0 + \frac{\frac{tV}{c} - r}{(\frac{tV}{c} - r) + r}V - c(-\frac{t^2V}{c} + \frac{2tV}{c} - \frac{r}{t})\right) - c(\frac{V(1-t)^2}{c} - r) = 0$$

- when $t \leq \sqrt{\frac{rc}{V}}$: as $X_F = 0$,

$$W = \frac{\frac{(\sqrt{V}-\sqrt{rc})^2}{c} - r}{(\frac{(\sqrt{V}-\sqrt{rc})^2}{c} - r) + r}\left[0 + \frac{\sqrt{\frac{rV}{c}} - r}{(\sqrt{\frac{rV}{c}} - r) + r}V - c(\sqrt{\frac{rV}{c}} - r)\right] - c(\frac{(\sqrt{V} - \sqrt{rc})^2}{c} - r) = 0$$

To address this issue, I additionally include social value s as in the Denicolò (2000). Since only the second innovation is assumed to have a private value for firms, only the second innovation is assumed to have a social value too. This s can represent consumer

[2] Denicolò (2000)'s definition includes social values of both innovations.

surplus generated from the final product or potential improvement and spillover from the innovation. For any values of t, the social welfare function is given as

$$W \equiv \frac{X_1}{X_1+r}\left[0+\frac{x_L+tX_F}{x_L+tX_F+r}(V+s)-cX_2\right]-cX_1=\frac{X_1}{X_1+r}\frac{x_L+tX_F}{x_L+tX_F+r}s$$

For the moment, assume firms invest as if $\sqrt{\frac{rc}{V}}<t\leq 1-\sqrt{\frac{rc}{V}}$ for all $t\in[0,1]$.[3] Plugging in all the values,

$$W=\frac{\frac{V(1-t)^2}{c}-r}{\frac{V(1-t)^2}{c}}\frac{\frac{tV}{c}-r}{\frac{tV}{c}}s=\left(1-\frac{rc}{V(1-t)^2}\right)\left(1-\frac{rc}{tV}\right)s$$

It is observed that W diverges to $-\infty$ as t approaches either 0 or 1. For brevity, let $a\equiv\frac{rc}{V}$. The above function has three zeros: $t=a,1\pm\sqrt{a}$. The FOC condition is given as

$$\frac{a[(1-t)^3-a(1-t)]-2a[t^2-at]}{t^2(1-t)^3}=a\frac{a(3t-1)-t^3+t^2-3t+1}{t^2(1-t)^3}=0$$

and the zero of the FOC, $t^*(a)$, is implicitly defined. As W is 0 at a and $1-\sqrt{a}$ and positive for some values, W has a maximum at $t^*(a)$. Therefore, if $t^*(a)$ is larger than the monopoly threshold $\sqrt{a}$, competition occurs at the socially optimal level of the government intervention. The following proposition characterizes optimal t maximizing the social welfare using this idea.

Proposition 3. *For given $a=\frac{rc}{V}$*

1. *The unique zero of FOC, $t^*(a)$, is larger than $1/3$.*

2. *For $\sqrt{a}<\frac{-1+\sqrt{3}}{2}$, allowing competition is more optimal. For $\sqrt{a}\geq\frac{-1+\sqrt{3}}{2}$, any $t\in[0,\sqrt{\frac{rc}{V}}]$ is optimal.*

3. $\frac{dt^*}{da}=-\frac{3t-1}{-3+2t-3t^2+3a}>0$

[3] Note that if $t\leq\sqrt{\frac{rc}{V}}$, W is constant as only the leader participates in the second race, which makes the expected profit in the first patent race constant with respect to t in the region. When $t\geq 1-\sqrt{\frac{rc}{V}}$, no firms enters the first race, meaning $W=0$.

Proof. First, I show that the FOC admits the unique solution $t^*(a)$, which shows there is only one maximum in the open interval $(0,1)$. $t^*(a)$ is a zero of

$$a(3t-1) = t^3 - t^2 + 3t - 1$$

The left hand side is a linear function passing $(1/3, 0)$. The derivative of the right hand side function is $3t^2 - 2t + 3 = 3(t-1/3)^2 + 8/3 > a$. Therefore, at most one solution exists in $(0,1)$. When $t = 1/3$, the left hand side is 0 and the right hand side is $-2/27$. Also, when $t = 1$, the left hand side is $2a$ and the right hand side is 2. Therefore, the two functions cross each other only at $t^*(a) > 1/3$.

Next, I determine the sign of FOC when $t = \sqrt{a}$, the threshold for the monopolistic investment.

$$\begin{aligned}
(1-\sqrt{a})^3 - 2a + a(3\sqrt{a}-1) &= 1 - 3\sqrt{a} + 3a - a\sqrt{a} - 2a + a(3\sqrt{a}-1) \\
&= 1 - 3\sqrt{a} + 2a\sqrt{a} \\
&= (\sqrt{a}-1)(2a + 2\sqrt{a} - 1)
\end{aligned}$$

If $2a + 2\sqrt{a} - 1 < 0$, the right derivative of W is positive. Therefore, the government can increase social welfare by increasing t. That is, competition increases social welfare. On the other hand, if $2a + 2\sqrt{a} - 1 > 0$, the right derivative of W is negative, which implies increasing t reduces the social welfare.

Finally, recall that $t^*(a)$ is implicitly defined as the zero of following $F(a,t)$,

$$F(a,t) = (1 - 3t + t^2 - t^3) + a(3t-1)$$

By the implicit function theorem,

$$\frac{dt}{da} = -\frac{dF/da}{dF/dt} = -\frac{3t-1}{-3+2t-3t^2+3a} > 0$$

The last inequality is from $t^*(a) > 1/3$ for all a and $-3 + 2t - 3t^2 + 3a = -3(t - \frac{1}{3})^2 + (3a - \frac{8}{3}) < 0$. The last inequality is from $\sqrt{V} \geq 2\sqrt{rc}$, or $a = \frac{rc}{V} \leq \frac{1}{4}$. $\square$

The first result is a technical one used to determine the sign of $\frac{dt^*}{da}$. As $a = \frac{rc}{V}$, the second result implies that if the value of innovation is large enough, competition is optimal. Finally, $\frac{dt^*}{da}$ shows how optimal protection should change according to the size of innovation. If V increases, a decreases making optimal protection stronger.

Recall that the social welfare function is given as

$$W = \frac{X_1}{X_1 + r} \, \frac{x_L + tX_F}{x_L + tX_F + r} \, s$$

This welfare function shows the trade-off generated by the level of forward patent protection $1 - t$. As the social value from the second innovation is fixed as s, the goal of the government is to a design patent policy to make the timing of the second innovation earlier to maximize social welfare. However, the government can increase the first period's investment only by reducing the second period's investment. Since $\frac{X}{X+r}$'s slope is decreasing in X, the government has to balance X_1 and $x_L + tX_F$, rather than choosing t which extremely allocates investment. This gives an explanation of the third part of the proposition (3). As V increases, incentives to invest increase relative more in the second race if t is fixed. This is because the prize of the second race is V and the expected prize of the first race is $(1-t)^2V$. Thus, to balance X_1 and $x_L + X_F$, t should become smaller to incentivize firms to invest more in the first race.

However, the government's ability to manipulate investment in each period is limited. The strongest protection that a government can offer is to monopolize the second patent race. Even if the government tries to provide a stronger protection, firms in the first race would not increase their investment as the expected profit at the beginning of the first race remains constant because only the winner will participate in the second race. Therefore, even small government protection satisfies $t \leq \sqrt{\frac{rc}{V}}$ relatively easy when V is small, which makes the government lose its leverage before sufficiently balancing investment between periods. Thus, the second result of the proposition (3) holds.

4 Extensions

In this chapter, two simple extensions of the baseline model are analyzed. First, a heterogeneity is introduced to races by making cost in each period differ. Second, the first patent is allowed to have a large non-zero intrinsic value.

4.1 Asymmetric cost

Let c_1 and c_2 be the cost of each patent race respectively. Once again, I add an assumption on V to ensure a monopoly firm would enter the innovation race. In the second race, the monopoly firm chooses x to maximize

$$\pi = \frac{xV}{x+r} - c_2 x$$

which leads to $x^* = \sqrt{\frac{rV}{c_2}} - r$ and $\pi^* = \left(\sqrt{V} - \sqrt{rc_2}\right)^2$

Therefore, at the first race, the monopoly firm chooses x' to maximize

$$\pi' = \frac{x'(\sqrt{V} - \sqrt{rc_2})^2}{x'+r} - c_1 x'$$

Similarly, $x'^* = \sqrt{\frac{r}{c_1}}\left(\sqrt{V} - \sqrt{rc_2}\right) - r$ and $\pi' = \left(\sqrt{V} - \sqrt{rc_1} - \sqrt{rc_2}\right)^2$. As $x'^* \geq 0$, $\sqrt{V} \geq \sqrt{rc_1} + \sqrt{rc_2}$ is required. This assumption also makes $x^* \geq 0$.

The following propositions characterize investments in both periods. The derivation of the result is the same with the previous propositions, for which the proofs are omitted.

Proposition 4. ***(Characterization of the second patent race)*** *For given $t \in [0, 1]$,*

- $x_L = \begin{cases} \frac{tV}{c_2} - \frac{t^2 V}{c_2} & \textit{when } t \geq \sqrt{\frac{rc_2}{V}} \\ \sqrt{\frac{rV}{c_2}} - r & \textit{otherwise} \end{cases}$

- $X_F = \begin{cases} \frac{tV}{c_2} - \frac{r}{t} & \textit{when } t \geq \sqrt{\frac{rc_2}{V}} \\ 0 & \textit{otherwise} \end{cases}$

- $\pi_L = \begin{cases} V(1-t)^2 & \textit{when } t \geq \sqrt{\frac{rc_2}{V}} \\ \left(\sqrt{V} - \sqrt{rc_2}\right)^2 & \textit{otherwise} \end{cases}$

- $x_L + tX_F = \begin{cases} \frac{tV}{c_2} - r & \textit{when } t \geq \sqrt{\frac{rc_2}{V}} \\ \sqrt{\frac{rV}{c_2}} - r & \textit{otherwise} \end{cases}$

Proposition 5. ***(Characterization of the first patent race)*** *For given $t \in [0,1]$,*

- $X_1 = 0$ *if* $1 - \sqrt{\frac{rc_1}{V}} < t$
- $X_1 = \frac{V(1-t)^2}{c_1} - r$ *if* $\sqrt{\frac{rc_2}{V}} < t \leq 1 - \sqrt{\frac{rc_1}{V}}$
- $X_1 = \frac{(\sqrt{V}-\sqrt{rc_2})^2}{c_1} - r$ *if* $t \leq \sqrt{\frac{rc_2}{V}}$

Therefore, the aggregated investment in the first race is a monotone decreasing function of t. Note that $\sqrt{\frac{rc_2}{V}} \leq 1 - \sqrt{\frac{rc_1}{V}}$ as $\sqrt{V} \geq \sqrt{rc_1} + \sqrt{rc_2}$.

The social welfare function defined below is again 0 for any value of t if the social value from the second innovation is not included.

$$W \equiv \frac{X_1}{X_1 + r}\left[0 + \frac{x_L + tX_F}{x_L + tX_F + r}V - c_2X_2\right] - c_1X_1$$

- when $t > 1 - \sqrt{\frac{rc_1}{V}}$: as $X_1 = 0$,

$$W = \frac{0}{0 + r}\left[0 + \frac{x_L + tX_F}{x_L + tX_F + r}V - c_2X_2\right] - c_1 \cdot 0 = 0$$

- when $\sqrt{\frac{rc_2}{V}} < t \leq 1 - \sqrt{\frac{rc_1}{V}}$: plugging in both values,

$$W = \frac{\frac{V(1-t)^2}{c_1} - r}{(\frac{V(1-t)^2}{c_1} - r) + r}\left(0 + \frac{\frac{tV}{c_2} - r}{(\frac{tV}{c_2} - r) + r}V - c_2(-\frac{t^2V}{c_2} + \frac{2tV}{c_2} - \frac{r}{t})\right)$$
$$-c_1(\frac{V(1-t)^2}{c_1} - r) = 0$$

- when $t \le \sqrt{\frac{rc_2}{V}}$: as $X_F = 0$,

$$W = \frac{\frac{(\sqrt{V}-\sqrt{rc_2})^2}{c_1} - r}{(\frac{(\sqrt{V}-\sqrt{rc_2})^2}{c_1} - r) + r}\left[0 + \frac{\sqrt{\frac{rV}{c_2}} - r}{(\sqrt{\frac{rV}{c_2}} - r) + r}V - c_2(\sqrt{\frac{rV}{c_2}} - r)\right. \\ \left. -c_1(\frac{(\sqrt{V} - \sqrt{rc_2})^2}{c_1} - r\right) = 0$$

For the moment, assume firms invests as if $\sqrt{\frac{rc_2}{V}} < t \le 1 - \sqrt{\frac{rc_1}{V}}$ for all t. Plugging in the optimal level of investment in each period to the social welfare function yields

$$W = \frac{V(1-t)^2 - rc_1}{V(1-t)^2}\frac{tV - rc_2}{tV}s = \left(1 - \frac{rc_1}{(1-t)^2 V}\right)\left(1 - \frac{rc_2}{tV}\right)s$$

For brevity, let $a_1 \equiv \frac{rc_1}{V}$ and $a_2 \equiv \frac{rc_2}{V}$. The above function has three zeros: $t = a_2, 1 \pm \sqrt{a_1}$. The FOC condition is

$$\frac{a_2[(1-t)^3 - a_1(1-t)] - 2a_1[t^2 - a_2 t]}{t^2(1-t)^3} = 0$$

and the zero of the FOC, $t^*(a_1, a_2)$, is implicitly defined. The following proposition characterizes optimal t maximizing the social welfare. Despite the asymmetry introduced, the message that optimal information friction allows competition for large innovation is still maintained.

Proposition 6. *For given $a_1 = \frac{rc_1}{V}$ and $a_2 = \frac{rc_2}{V}$*

1. *For large V, the global maximizer $t^*(a_1, a_2)$ satisfies FOC condition and allowing competition is more optimal.*

2. *Additionally assume $4a_1 - 12a_2 + 9a_2^2 < 0$. Then, for large V, $\frac{dt}{da_1} < 0$ and $\frac{dt}{da_2} > 0$.*

Proof. $t^*(a_1, a_2)$ is implicitly defined as the zero of

$$F(t, a_1, a_2) := a_2[(1-t)^3 - a_1(1-t)] - 2a_1[t^2 - a_2 t] = 0$$

When a_1 and a_2 are fixed, $F(0, a_1, a_2) = a_2(1 - a_1) > 0$ and $F(1, a_1, a_2) = -2a_1(1 - a_2) < 0$. Thus, at least one solution exists if a_1 and a_2 are fixed.

Now, determine the sign of FOC when $t = \sqrt{a_2}$, the threshold for the monopolistic investment.

$$\begin{aligned}
& a_2[(1-\sqrt{a_2})^3 - a_1(1-\sqrt{a_2})] - 2a_1(a_2 - a_2\sqrt{a_2}) \\
= \; & a_2(1-\sqrt{a_2})[(1-\sqrt{a_2})^2 - a_1] - 2a_1a_2(1-\sqrt{a_2}) \\
= \; & a_2(1-\sqrt{a_2})[(1-\sqrt{a_2})^2 - 3a_1]
\end{aligned}$$

As a_1 and a_2 converge to 0 as V increases, for sufficiently large V, the above value is positive. This implies the government can increase social benefit by increasing t. Therefore, weakening protection to ensure competition is optimal.

If V is large, the global maximizer exists in $[\sqrt{a_2}, 1-\sqrt{a_1}]$ since W is locally increasing in t at $\sqrt{a_2}$ and $W = 0$ for $t = 1-\sqrt{a_1}$. Additionally, W is constant on $[0, \sqrt{a_2}]$ and $[1-\sqrt{a_1}, 1]$. Therefore the global maximizer $t^*(a_1, a_2)$ exists in $[\sqrt{a_2}, 1-\sqrt{a_1}]$ and it satisfies the FOC condition.

To apply the implicit function theorem, I use the following derivatives:

$$\begin{aligned}
\frac{\partial F}{\partial t} &= -3a_2(1-t)^2 + 3a_1a_2 - 4a_1t < 0 \\
\frac{\partial F}{\partial a_1} &= -a_2 + 3a_2t - 2t^2 < 0 \\
\frac{\partial F}{\partial a_2} &= (1-t)^3 - a_1 + 3a_1t > 0
\end{aligned}$$

The discriminant of first partial derivative is

$$4(3a_2 - 2a_1)^2 + 12a_2(3a_1a_2 - 3a_2) = 4a_1(4a_1 - 12a_2 + 9a_2^2) < 0$$

By the assumption, the discriminant is negative and this partial derivative does not have any real roots and its value calculated at $t = 0$ is $-3a_2(1-a_1) < 0$. Therefore, this partial is negative on $[0, 1]$.

The discriminant of the second partial derivative is

$$9a_2^2 - 8a_2 = a_2(9a_2 - 8) < 0$$

as $a_2 \to 0$ as $V \to \infty$ Therefore, this partial derivative does not have any real roots. Also, its value calculated at $t = 0$ is negative. Therefore, the second derivative is negative on $[0, 1]$.

Finally, I analyze the last derivative. $(1-t)^3 \geq 0$ on $t \in [0, 1]$ and $-a_1 + 3a_1 t \geq 0$ if $t \geq \frac{1}{3}$. Also, if $V \to \infty$, the effect of $-a_1 + 3a_1 t$ to $\frac{\partial F}{\partial a_2}$ on $[0, \frac{1}{3}]$ would be negligible making the derivative positive for all $t \in [0, 1]$.

By the implicit function theorem

$$\begin{cases} \frac{dt}{da_1} = -\frac{\partial F/\partial a_1}{\partial F/\partial t} < 0 \\ \frac{dt}{da_2} = -\frac{\partial F/\partial a_2}{\partial F/\partial t} > 0 \end{cases}$$

□

$4a_1 - 12a_2 + 9a_2^2 < 0$ condition is added to make the exposition simple. This implies $F(t, a_1, a_2)$ is monotone in t on $[0, 1]$. This condition allows us to avoid directly computing $t^*(a_1, a_2)$ and calculating all values of derivatives to determine how changes in a_1 and a_2 alter the optimal government intervention. However, V's effect on $t^*(a_1, a_2)$ is ambiguous even with this assumption. Increase in V moves a_1 and a_2 to the same direction, yet a_1 and a_2 move $t^*(a_1, a_2)$ to different direction. Therefore, without additional assumption on r, c_1, and c_2, V's impact remains undetermined. Nevertheless, one of the main result of the baseline model is still maintained. For sufficiently large innovation, the optimal government ensures competition occur in the equilibrium. Also, it is worth noting that with the additional assumption, if FOC's sign is negative at $\sqrt{a_2}$, the monopoly threshold, allowing competition is suboptimal. This is due to the fact that the FOC's zero is unique by monotonicity of $F(t, a_1, a_2)$ in t.

4.2 First innovation with a large value

Now, the baseline model is extended to the case when the first innovation has non-zero intrinsic value of flow rV_1. Recall that the social welfare function of the baseline model is

$$W = \frac{X_1}{X_1 + r} \frac{x_L + tX_F}{x_L + tX_F + r} s$$

For the moment, assume that the government does not intervene in the patent races. Then X_1 and $x_L + tx_F$ are determined by V_1 and V_2 respectively where the flow of rV_2 is the prize of the second race. Additionally, assume $V_1, V_2 \geq rc$, so that both innovation is worth investing in themselves to avoid the case of no first race investment. Due to the assumption that the social value of innovation is concentrated on the second innovation, the government wants to balance investment between periods. If $V_2 > V_1 = 0$, the government can use information friction to transfer investment from the second race to the first race, which is the result of the main analysis. However, if V_1 is sufficiently large, firms will have sufficient incentive to invest in the first race even without the government intervention. The following proposition shows that this intuition is true.

Proposition 7. *For fixed V_2, if V_1 is sufficiently large, it is optimal for the government not to intervene in the patent race. That is, $t = 1$ is optimal.*

Proof. The second patent race remains the same. At the beginning of the first patent race, a typical firm i's profit is given as

$$\pi_i = \frac{x_i(\pi_L + V_1)}{X_1 + r} - cx_i$$

which is 0 due to the free entry condition. Therefore, the aggregated level of first investment is

- $X_1 = \frac{V_1 + V_2(1-t)^2}{c} - r$ if $\sqrt{\frac{rc}{V_2}} < t$
- $X_1 = \frac{V_1 + (\sqrt{V_2} - \sqrt{rc})^2}{c} - r$ if $t \leq \sqrt{\frac{rc}{V_2}}$

by using the result from the proposition (1). Note that $V_1, V_2 \geq rc$ is assumed to avoid the case $X_1 = 0$.

Once again, for the moment, ignore the monopolistic case and plug in values of investment in each race, which leads to

$$W = \frac{V_1 + V_2(1-t)^2 - rc}{V_1 + V_2(1-t)^2}\ \frac{tV_2 - rc}{tV_2}\ s$$

Take logarithm on the both sides of the equation and take the derivative with respect to t.

$$(\log W)' = \frac{W'}{W} = \frac{2V_2(t-1)}{V_1 + V_2(1-t)^2 - rc} - \frac{2V_2(t-1)}{V_1 + V_2(1-t)^2} + \frac{V_2}{tV_2 - rc} - \frac{V_2}{tV_2}$$

$\frac{V_2}{tV_2-rc} - \frac{V_2}{tV_2} \geq 0$ holds for any $t > \sqrt{\frac{rc}{V_2}}$, where $\sqrt{\frac{rc}{V_2}}$ is the monopoly threshold. It can be observed that $\frac{V_2}{tV_2-rc} - \frac{V_2}{tV_2} = \frac{rcV_2}{(tV_2-rc)tV_2} \geq \frac{rcV_2}{(V_2-rc)V_2} = \frac{rc}{V_2-rc}$. Therefore, if a uniform bound of $\frac{2V_2(t-1)}{V_1+V_2(1-t)^2-rc} - \frac{2V_2(t-1)}{V_1+V_2(1-t)^2}$ can be set on $t \in [\sqrt{\frac{rc}{V_2}}, 1]$, $\frac{W'}{W} \geq 0$ will hold. This will imply W is increasing on $(\sqrt{\frac{rc}{V_2}}, 1]$, which makes $t = 1$ optimal.

$$\begin{aligned}
\left|\frac{2V_2(t-1)}{V_1 + V_2(1-t)^2 - rc} - \frac{2V_2(t-1)}{V_1 + V_2(1-t)^2}\right| &\leq \frac{2V_2(1-t)}{V_1 + V_2(1-t)^2 - rc} + \frac{2V_2(1-t)}{V_1 + V_2(1-t)^2} \\
&\leq \frac{2V_2}{V_1 - rc} + \frac{2V_2}{V_1} \qquad \text{for any } t \in [\sqrt{\frac{rc}{V_2}}, 1] \\
&\to 0 \qquad \text{as } V_1 \text{ goes to } \infty
\end{aligned}$$

Since $\frac{2V_2(t-1)}{V_1+V_2(1-t)^2-rc} - \frac{2V_2(t-1)}{V_1+V_2(1-t)^2}$ can be uniformlly bounded as above, for sufficiently large V_1, $|\frac{2V_2(t-1)}{V_1+V_2(1-t)^2-rc} - \frac{2V_2(t-1)}{V_1+V_2(1-t)^2}| \leq \frac{rc}{V_2-rc}$ holds. This implies $(\log W)'$ is positive on $(\sqrt{\frac{rc}{V_2}}, 1]$. As W is a continuous non-negative function, this implies W' is positive on $(\sqrt{\frac{rc}{V_2}}, 1]$, making $t = 1$ optimal. □

The proposition (7) shows another limitation of the policy. Information friction works in only one way: allocating investment in the second race to the first race. Therefore, if $V_1 = 0$, government intervention is effective and increases social welfare. However, when V_1 is large, firms would be motivated enough to innovate in the first race without the government's intervention.

5 Conclusion

In this paper, I constructed a model based on Denicolò (2000) to investigate information friction's effect on sequential innovation. This paper finds how optimal government protection should be designed depending on the innovation's value.

When the social value is concentrated on the second innovation, the government wants to balance investment between the two periods. However, this ability to manipulate investment in each period is restricted since strong protection bars entry of followers and makes the second innovation race monopoly. This goal of the government and limitation shape how optimal information friction should be set as the value of innovation changes. In symmetric races, competition is optimal when value of innovation is large. Also, the degree of protection should become stronger as the value of the innovation increases.

The message that competition is beneficial for large innovation seems robust even when costs are asymmetric. Also, with additional assumptions on parameters, optimal government protection level can be analyzed. However, these results can only be applied to innovations with the small first innovation value. If the the value of first innovation is sufficiently large compared to the second one, the government should not intervene in the races.

One of the main drawbacks of this paper is that this does not take account of replacement effect. Since the patents' statutory life is set to be infinity and the first patent's value is 0 in the baseline model, replacement effect is not explicitly considered in the paper. However, the result would be different with the effect. For instance, even if the first patent's value is large, it can completely become obsolete by the second innovation. In this case, this would eventually make the expected payoff of the first innovation smaller, which changes incentives of firms and possibly the optimal government intervention. Therefore, with replacement effect, the optimal level of protection may have to be stronger than this paper suggests. Another drawback of this paper is that it does not completely characterize the equilibrium when costs are asymmetric. To avoid complex calculations, an assumption is added to characterize the optimal intervention.

Possible future research may include investigating the optimal policy when replacement effect exists. As mentioned before, replacement effect may alter the optimal level of intervention, changing the result of this paper. Also, another would be examining how intervention should be designed when the first patent's value is moderate. It is shown that intervention is not optimal when the first patent's value is large enough. However, patent values between 0 and the large value are not completely studied. As the government wants to balance investment between periods, government intervention would decrease as the first patent's value increases. Completely characterizing the optimal policy level with respect to the first patent value can be a next step. Finally, the social benefits were assumed to be concentrated on the second innovation. However, it is plausible that the first innovation has an intrinsic social value itself. Adding the first innovation's social value is likely to make the government increase protection to the first patent. Determining how exactly the first innovation's social value would change the government's policy is left for the future research.

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국문초록

본 논문은 순차적 혁신에서 정보 마찰을 통한 선행 특허 보호의 효과를 분석한다. 순차적 혁신을 두 연속된 특허 경주로 간주한 모형에서 최종 혁신의 가치에 따라 어느 수준의 특허 보호가 최적인지 알아본다. 사회적 가치가 최종 혁신에 집중되어 있을 때, 정부는 각 특허 경주마다 투자를 고르게 할당할 유인이 있으며, 이는 최적 특허 보호 수준에 대한 설명을 제공한다. 충분히 혁신의 가치가 큰 경우 최적 보호 수준에서는 경쟁이 일어나며, 이는 두 특허 경주의 비용구조에 이질성이 있더라도 성립한다. 단, 첫 번째 특허의 가치가 충분히 큰 경우에는 정부 개입이 불필요한 것으로 나타나는데, 이는 본 논문에서 다룬 정보 마찰을 이용한 정책이 두 번째 경주의 투자를 첫 번째 경주의 투자로 이전하는 방식이기 때문이다.

주요어 : 순차적 혁신, 특허 경주, 선행 특허 보호, 정보 마찰
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