Patent Portfolio Race and Secrecy

Illoong Kwon*
State University of New York at Albany

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Abstract

When firms can protect their innovations by secrecy or lead-time, the additional effect of patent protection is not obvious. This paper shows that when firms compete for a single innovation, patent protection still increases R&D investment but decreases social welfare due to over-investment. However, when firms compete for multiple complementary patents (called a patent portfolio), patent protection decreases R&D investment and decreases social welfare due to under-investment. If firms cannot rely on secrecy, patent protection increases investment regardless of whether firms compete for a single patent or for a patent portfolio.

1 Introduction

Contrary to conventional wisdom, many empirical studies have found that firms, on average, do *not* heavily rely on patents in appropriating the returns of their innovations.[1] Recent surveys by Levin et. al. (1987) and by Cohen et. al. (2000) also show that the majority of firms protect the

*Contact: Illoong Kwon, Department of Economics, SUNY-Albany, 1400 Washington Ave., Albany, NY 12222. Email: ikwon@albany.edu I would like to thank Nadav Levy, Michael Jerison, and seminar participants at SUNY-Albany for helpful comments and suggestions. All remaining errors are mine.

[1] See, for example, Mansfield (1986) and Mansfield et al. (1981).

profits from their innovation with secrecy and lead-time rather than with patents[2]. Despite these studies, patent protection is still generally regarded as a cornerstone for innovation, and has been greatly strengthened in the last few decades, as highlighted by the 1982 formation of a centralized appellate court, the Court of Appeals for the Federal Circuit.

Surprisingly, however, the economics literature has largely ignored the effect of patent protection when firms can already rely on secrecy or lead-time[3]. Instead, most previous studies on patent policy have assumed that innovation would suffer from imitation in the absence of patent protection.

In this paper, I show that when firms can rely on secrecy, patent protection has very different effects on firms' R&D investment and social welfare depending on whether firms compete (i) for a single innovation or (ii) for multiple complementary innovations (e.g. hardware and software). In the former case, patent protection increases R&D investment but decreases social welfare due to over-investment. In the latter case, patent protection *decreases* R&D investment and decreases social welfare due to under-investment. As will be discussed later, these results provide rich policy implications, and explain why stronger patent policy has increased the patent propensity in particularly those industries that do *not* regard patent as effective, called the 'patent paradox'.

What drive these results are two types of exclusions that patents provide. First, patents prevent imitation by others. I call this *defensive exclusion*. Second, even if someone else has made the same innovation independently (without imitation), patents still prevent the person from using the innovation. I call this *offensive exclusion*. Secrecy differs from patent protection because it provides defensive exclusion, but not offensive exclusion.

[2]For example, in the survey by Cohen et. al. (2000), an average firm reports that secrecy is 51% effective as an appropriability mechanism, while a patent is 35% effective. In particular, firms in the semiconductor industry report that secrecy is 60% effective while a patent is only 27% effective.

[3]There are some studies on secrecy when patent protection is not complete. For example, when patent application reveals information that facilitates future imitation, firms may choose to keep innovation secret or suppress innovation altogether. See, for example, Scotchmer and Green (1990), Anton and Yao (2004), and Denicolo and Franzoni (2004). In contrast, this paper considers the role of secrecy when patent protection is strong and broad enough that it does not facilitate imitation or subsequent innovations by other firms.

Defensive exclusion not only prevents others' imitation, but also reduces a firm's own incentive to imitate (or *free-ride*) other firms' innovations. Therefore, defensive exclusion promotes research investment.

Offensive exclusion preempts other firms' independent success, and prevents competition in the product market. Because the sum of oligopoly profits is generally smaller than the monopoly profit, offensive exclusion prevents *profit dissipation* in the product market, and induces more research investment. However, when firms compete for multiple complementary innovations simultaneously, or an R&D portfolio, the offensive exclusion of a single patent can hold up other firms by preventing them from using their own complementary innovations[4]. The danger of this *hold-up effect* decreases research investment.

When firms can rely on secrecy, patent protection offers only offensive exclusion in addition. If firms compete for a single innovation, offensive exclusion prevents profit dissipation without generating hold-up effects, and induces more R&D investment. However, if firms compete for multiple complementary innovations, the hold-up effect dominates the profit dissipation effect, and reduces firms' incentives for R&D.

Few previous studies have distinguished between the defensive exclusion and the offensive exclusion of patents. Most early studies have focused on the prevention of imitation (i.e. defensive exclusion) as the main role of patent protection. Then, more recent studies (e.g. Shapiro 2001 and Hall and Ziedonis 2000) have pointed out the potential negative effects of patent on research investment due to the *hold-up effect* (i.e. offensive exclusion). As firms require access to increasingly more complementary patents (called a patent thicket), there are also growing debates as to whether patent protection can slow down innovations because of the hold-up effect. However, there exist few equilibrium models that address *both* defensive and offensive exclusion, and analyzes when and where one type of exclusion matters more than the other.

It is worth emphasizing that if firms can *not* protect their innovations by secrecy or lead-time,

[4]For example, in 2004, NTP successfully sued RIM, the maker of the BlackBerry hand-held wireless e-mail device, for infringing on its patent on wireless communication technology. This case almost halted the entire BlackBerry service, even though RIM owned most other innovations in hardware and software.

this paper shows that patent protection *always* increases R&D investment regardless of whether firms compete for a single patent or for multiple complementary patents (called a patent portfolio or a patent thicket). In other words, when firms cannot rely on secrecy, the positive effects of defensive exclusion always dominate the negative hold-up effect by offensive exclusion. However, as discussed above, if firms can rely on secrecy, the negative hold-up effect dominates, and patents do reduce R&D investment and social welfare.

Scotchmer (1991), O'Donoghue et. al. (1998), and Bessen and Maskin (2006) have also studied the potentially negative effect of stronger (or broader) patent protection in the context of cumulative (or sequential) innovations where one innovation builds on previous innovations. In these models, firms typically invest in at most one project in a given period. This paper departs from these models by allowing firms to invest in multiple complementary innovations at the same time[5]. Therefore, while these previous studies describe competition in a given technology/product line (e.g. computer hard drive), this paper captures the complementarity between two different technologies (such as hardware and software or engine and brakes). Furthermore, in these models, there is often no difference between secrecy and patent, as the other firm cannot independently succeed in the subsequent innovation without knowing the previous innovation. Therefore, these models cannot distinguish between defensive exclusion and offensive exclusion of patents.

The rest of the paper is organized as follows. Section 2 provides a basic model. Section 3 considers a single patent race, and analyzes the role of secrecy. Section 4 introduces an R&D portfolio race, and analyzes market equilibria. The welfare effects of patent protection are considered in section 5. Section 6 discusses policy implications and concludes.

2 The Model

There are two symmetric firms ($i = 1, 2$). Each firm invests in two research projects ($k = A, B$) simultaneously. Let us denote firm $i's$ R&D investment in project k by I_k^i.

[5] There is a series of studies that look at market bias in relative investment between risky and safe projects (e.g. Dasgupta and Maskin 1987 and Cabral 1994). These studies consider only relative investment holding total investment constant, and do not consider complementary projects.

The projects can either succeed or fail. Let us denote firm $i's$ probabilities of success in project A and B by $p(I_A^i)$ and $q(I_B^i)$ respectively, where $p' > 0$, $q' > 0$, $p'' < 0$, $q'' < 0$, $p < \frac{1}{2}$, and $q < \frac{1}{2}$ for all $I \geq 0$. Throughout the paper, I assume that the second order conditions for a symmetric equilibrium are satisfied.[6] The assumptions $p < \frac{1}{2}$ and $q < \frac{1}{2}$ capture the inherent risk of R&D investment, and guarantees that the probability of at least one firm succeeding is still less than one.

The success of one project alone generates *no* social value. However, the joint success of both projects generates the positive social value V (> 0). In this sense, the two projects are *complementary* in creating the values of a product(s), but independent in the probability of success.[7] For example, project A can be on hardware, and project B on software. Thus, we focus on the value complementarity of two technologically independent innovations. In contrast, most previous studies (e.g. Scotchmer 1991, Bessen and Maskin 2006) have focused on technological complementarity where the success of one innovation leads to the success of another innovation.

Under patent protection, if both firms succeed in the same project, they get the patent with equal probability. When there is no patent protection, the paper considers two opposite cases. In the first case, firms can imitate others' success at no cost. In the second case, firms can keep their innovation secret and prevent imitation.

For simplicity, I assume that licensing is not feasible. However, as shown in the appendix, allowing licensing or a non-assertion agreement does not change the qualitative results of the paper.

If a firm cannot use both innovations from projects A and B, I normalize the profit of the firm to zero. If only one firm can use both innovations from projects A and B, it can appropriate all the social value of the innovations (V). If both firms can use the innovations from projects A and

[6] When $p(.) = q(.)$, the second order conditions in the rest of the paper are satisfied if $-\frac{(p')^2}{p''} < \frac{p(1-p^2)}{(1+p^2)}$. For example, if $p(I) = q(I) = x^T$ where $0 < T < \frac{1}{2}$, the second order conditions are satisfied if $p < \sqrt{1-2T}$.

[7] Bessen and Maskin (2006) defines that innovations are complementary if the probability of innovation increases with the number of firms investing in the same innovation. Note, however, that according to our definition of complementarity, they are considering the *substitutable* projects because in their model, subsequent innovations make the preceding innovations completely obsolete.

B, they compete in the product market. Then, each firm makes profit v where $0 \leq v < \frac{V}{2}$, and the consumer surplus is $V - 2v$. That is, the sum of duopoly profits is less than the monopoly profit, and there is no deadweight loss[8].

3 Single Patent Race

For a benchmark, I first consider a standard single patent race model. Alternatively, one can assume that projects A and B are independent in creating values. Suppose that each firm invests in a single project A. For this section, assume that the success of project A alone can create social value/profit of V (> 0).

Imitation If project A is *not* protected by patent or by secrecy, each firm can imitate the other's success. Then, if at least one firm succeeds in the project (with probability $p_1 + p_2 - p_1 p_2$), both firms can use the successful outcome of project A, and make a profit of v $(0 \leq v < \frac{V}{2})$.

Under imitation, firm $i's$ expected profit (denoted by π_i^M) is as follows:

$$\pi_i^M = (p_i + p_j - p_i p_j)v - I_A^i \tag{1}$$

where $p_i = p(I_A^i)$ and $i, j = 1, 2$ and $j \neq i$.

From the first order conditions and the symmetry of the model, the (symmetric) market equilibrium (denoted by I_A^M) is determined as follows:

$$\frac{\partial \pi_i^M}{\partial I_A^i} = p'(I_A^M)(1 - p(I_A^M))v - 1 = 0 \tag{2}$$

Secrecy Now suppose that even without patent, firms can protect their innovation by secrecy. Recall that secrecy prevents imitation (defensive exclusion), but does not prevent the other firm from using its own independent success. Therefore, if firm i is the only firm that succeeds in project A (with probability $p_i(1 - p_j)$), it can appropriate the full social value V. However, if both

[8] Allowing deadweight loss does not change the qualitative results of this paper.

firms succeed independently (with probability $p_i p_j$), each firm earns only v where $v < \frac{V}{2}$ Then, firm $i's$ expected profit under secrecy (denoted by π_i^S) is as follows:

$$\pi_i^S = p_i(1 - p_j)V + p_i p_j v - I_A^i \tag{3}$$

From the first order conditions and the symmetry of the model, the market equilibrium under secrecy (denoted by I_A^S) is determined as follows:

$$\frac{\partial \pi_i^S}{\partial I_A^i} = p'(I_A^S)(1 - p(I_A^S))V + p'(I_A^S)p(I_A^S)v - 1 = 0 \tag{4}$$

From the comparison between (2) and (4), one can see that the marginal returns to investment are larger under secrecy than under imitation, because

$$\left.\frac{\partial \pi_i^S}{\partial I_A^i}\right|_{I_A^1=I_A^2=I_A^M} - \left.\frac{\partial \pi_i^M}{\partial I_A^i}\right|_{I_A^1=I_A^2=I_A^M} = \left[p'(I_A^M)(1 - p(I_A^M))(V - v)\right] + \left[p'(I_A^M)p(I_A^M)v\right] > 0 \tag{5}$$

where the inequality follows from $V > v$ and $v \geq 0$. Therefore, $I_A^M < I_A^S$.

Equation (5) captures the additional marginal returns from the *defensive exclusion* of secrecy. First, secrecy prevents imitation by the other firm and the resulting loss of profits, which is captured by the first bracket in (5). Second, secrecy prevents firm i from itself imitating or free-riding on the other firm's success, which is captured by the second bracket in (5). Therefore, firms would invest more under secrecy than under imitation.

Patent Now suppose that project A is protected by a patent. Thus, if firm i wins a patent, it can prevent firm j from using even its own independent outcome of project A. I call this *offensive exclusion*. Recall that if both firms succeed in the same project, each firm wins the patent with equal probability. Therefore, the expected profit of firm i under patent (denoted by π_i^P) is as follows:

$$\pi_i^P = p_i(1 - p_j)V + \frac{p_i p_j}{2}V - I_A^i \tag{6}$$

From the first order conditions and the symmetry of the model, the market equilibrium under patent (denoted by I_A^P) is determined as follows:

$$\frac{\partial \pi_i^P}{\partial I_A^i} = (p'(I_A^P) - p'(I_A^P)p(I_A^P))V + \frac{p'(I_A^P)p(I_A^P)}{2}V - 1 = 0 \tag{7}$$

From the comparison between (4) and (7), the marginal returns to investment under patent are larger than those under secrecy because

$$\left.\frac{\partial \pi_i^P}{\partial I_A^i}\right|_{I_A^1 = I_A^2 = I_A^S} - \left.\frac{\partial \pi_i^S}{\partial I_A^i}\right|_{I_A^1 = I_A^2 = I_A^S} = p'(I_A^S)p(I_A^S)(\frac{V}{2} - v) > 0 \tag{8}$$

where the inequality follows from $v < \frac{V}{2}$.

Under secrecy, if both firms succeed in the innovations, they must split profits through competition. However, under patent, only one firm gets the monopoly profit. Since the monopoly profit is larger than the sum of duopoly profits (called the *profit dissipation* effect), patent protection provides larger marginal returns to investment. In other words, even when firms can already rely on secrecy, patent protection still increases R&D investment.

Note that the distinction between secrecy and patent allows us to decompose the role of patent in a single patent race into three components. Patent protection *(i)* prohibits others' imitation of a firm's own research, and *(ii)* removes a firm's own incentive to free-ride on others' research. Furthermore, the patent *(iii)* prevents the profit dissipation from competition, based on 'offensive exclusion'. Secrecy shares the first two properties, but not the third one.

Even though patent protection provides more research incentives than secrecy in a single patent race, it does not necessarily mean patent protection improves social welfare.

Welfare Analysis For welfare analysis, first consider the socially optimal amount of investment. Because firms are competing for the same innovation, society enjoys V if at least one firm succeeds. Then, a social planner would maximize the following expected social surplus:

$$S = (p_1 + p_2 - p_1 p_2)V - I_A^1 - I_A^2 \tag{9}$$

From the first-order conditions and symmetry, the socially optimal investment (denoted by I_A^*) is determined by

$$\frac{\partial S}{\partial I_A^i} = (p'(I_A^*) - p'(I_A^*)p(I_A^*))V - 1 = 0 \tag{10}$$

From the comparison among (2), (4), (7), and (10), it is straightforward to establish the following proposition.

Proposition 1 *In a single patent race for project A, $I_A^P > I_A^S \geq I_A^* > I_A^M$. Equality holds if $v = 0$. Thus, if firms can already rely on secrecy, patent protection reduces social welfare due to over-investment.*

Proof. See appendix. ■

Firms *under*-invest when imitation is possible, i.e. $I_A^M < I_A^*$, as is often explained by the 'free-rider' problem. However, firms *over*-invest when patent applies, i.e. $I_A^P > I_A^*$, as often explained by the 'business-stealing' effect (see, e.g., Loury 1979 or Lee and Wilde 1980). Therefore, in comparison with imitation (or when firms cannot rely on secrecy), patent protection *may* increase social welfare if, roughly speaking, the amount of over-investment with patent is relatively smaller than the degree of under-investment with imitation.

Note, however, that when firms can rely on secrecy, introducing (or strengthening) patent protection *decreases* social welfare because it exacerbates the over-investment problem (i.e. $I_A^P > I_A^S \geq I_A^*$). Intuitively, firms still over-invest under secrecy. This is because given the success of firm j, society does not value firm $i's$ additional success, but firm i still values the success as long as $v > 0$. As shown above, patent protection induces firms to invest even more (due to the elimination of the profit dissipation effect), and thus reduces social welfare.

Therefore, in a single patent race, patent protection always increases firms' investment. However, the welfare and policy implications are different depending on whether firms can rely on secrecy.

One caveat is that if firms cannot appropriate all the social returns, firms may under-invest even with patents. Then, patent protection can improve social welfare even when firms can rely on secrecy. I will discuss policy implications later in more details.

4 Patent Portfolio Race

Now suppose that firms compete in two complementary projects simultaneously. Like in the previous section, I distinguish the effect of patent protection between (i) when firms can protect their research outcome by *secrecy* and (ii) when firms cannot prevent *imitation* in the absence of patent protection.

Secrecy Under secrecy, firm i can now guarantee a profit of V if it is the only firm that succeeds in *both* projects (with probability $p_i q_i (1 - p_j q_j)$). If both firms succeed in both projects (with probability $p_i q_i p_j q_j$), each firm earns a profit of v. Thus, the expected profit of firm i (as denoted by π_i^S) is as follows:

$$\pi_i^S = p_i q_i (1 - p_j q_j) V + p_i q_i p_j q_j v - I_A^i - I_B^i \tag{11}$$

where $p_i = p(I_A^i)$ and $q_i = q(I_B^i)$.

From the first order conditions and symmetry, the market equilibrium under secrecy (denoted by I_A^S and I_B^S) is determined as follows:

$$\frac{\partial \pi_i^S(I_A^S, I_B^S)}{\partial I_A^i} = p_i' q_i \left[V - p_j q_j (V - v) \right] - 1 = 0 \tag{12}$$

$$\frac{\partial \pi_i^S(I_A^S, I_B^S)}{\partial I_B^i} = p_i q_i' \left[V - p_j q_j (V - v) \right] - 1 = 0 \tag{13}$$

where $p_i' = p'(I_A^S)$ and $q_i' = q'(I_B^S)$.

Patent Now consider the introduction of patent protection for both projects. For comparison with secrecy, one must consider first whether firms would file for patents even when they can keep the outcome of projects secret.

Lemma 1 *Even if firms can keep the outcome of projects secret, filing for patents is a strictly dominant strategy.*

Proof. Suppose firm j is filing for a patent with a positive probability. Then, there is a positive probability that firm i may not be able to use the outcome of a project even when it succeeds in the project. If firm j is not filing for a patent, firm i can make a monopoly profit V instead of a duopoly profit v ($< \frac{V}{2}$) when both firms succeed. Therefore, firm i is strictly better off by filing for the patent. ■

Thus, this paper differs from previous studies where firms may choose secrecy in order to hide information in patent documents (see footnote 3). Note that when firms can keep the research outcome secret, firms file for patents not to prevent imitation but to defend their right to use their own research outcome.

With patent protection, firm i can appropriate from the complementarity of the two projects only if it wins both patents. Therefore, the expected profit of firm i (denoted by π_i^P) is as follows:

$$\pi_i^P = \left(p_i(1-p_j) + \frac{p_i p_j}{2}\right)\left(q_i(1-q_j) + \frac{q_i q_j}{2}\right) V - I_A^i - I_B^i \tag{14}$$

From the first order conditions and symmetry, the market equilibrium under patents (denoted by I_A^P and I_B^P) is determined as follows:

$$\frac{\partial \pi_i^P(I_A^P, I_B^P)}{\partial I_A^i} = p_i' q_i (1 - \frac{p_j}{2})(1 - \frac{q_j}{2})V - 1 = 0 \tag{15}$$

$$\frac{\partial \pi_i^P(I_A^P, I_B^P)}{\partial I_B^i} = p_i q_i' (1 - \frac{p_j}{2})(1 - \frac{q_j}{2})V - 1 = 0 \tag{16}$$

where $p_i' = p'(I_A^P)$ and $q_i' = q'(I_B^P)$.

Secrecy vs. Patent I am now ready to compare market equilibria under secrecy and under patents. The following proposition shows, in contrast to the single patent race case, that patent protection *reduces* research investment in both projects.

Proposition 2 *When firms can rely on secrecy, patent protection reduces research investment in both projects A and B. That is,* $I_A^P < I_A^S$ *and* $I_B^P < I_B^S$.

Proof. See appendix. ■

To gain intuition, let us compare the first order conditions under patent protection, (15) and (16), with those under secrecy, (12) and (13). Without loss of generality, consider the first order conditions for project A, (15) and (12), as follows:

$$\frac{\partial \pi_i^P(I_A^S, I_B^S)}{\partial I_A^i} - \frac{\partial \pi_i^S(I_A^S, I_B^S)}{\partial I_A^i} = \left[\frac{p_i' q_i p_j q_j}{2}\left(\frac{V}{2} - v\right)\right] - \left[p_i'(1-p_j)\frac{q_i q_j}{2}V\right] - \left[q_i(1-q_j)\frac{p_i' p_j}{2}V\right] - \left[\frac{p_i' q_i p_j q_j}{2}v\right] \tag{17}$$

The first bracket in (17) captures the same *profit dissipation effect* as in the single patent race. Suppose that either firm 1 or 2 wins both patents (with probability $\frac{p_i q_i p_j q_j}{2}$). In either case, each firm would earn v under secrecy. Under patent, however, each firm would earn V with probability $\frac{1}{2}$. Since the monopoly profit is larger than the sum of duopoly profits, $\frac{V}{2} - v > 0$. In other words, patent, unlike secrecy, prevents competition in the product market and provides larger marginal returns to investment.

The second bracket, however, captures the negative *hold-up effect* that does not exist in the single patent race. For example, suppose that firm i succeeds in both projects, and that firm j succeeds in project B only (with probability $p_i(1-p_j)q_i q_j$). Then, firm i will win the patent for project A for sure, but firm j can still win the patent for project B with probability $\frac{1}{2}$. In such a case, firm i cannot make any profit even though it is the only firm that has succeeded in both projects. In other words, firm $j's$ patent for project B can block firm i from making profits. Firm $j's$ patent in this case is often called a 'blocking patent'. Recall that under secrecy, firm i could make profit V because it is the only firm that succeeded in both projects. Therefore, compared with secrecy, the possibility of the hold-up effect under patent reduces marginal returns to investment.

The third bracket in (17) captures the same *hold-up effect* when firm i succeeds in both projects but firm j wins the patent for project A without succeeding in project B (with probability $q_i(1-q_j)\frac{p_i p_j}{2}$).

The last bracket in (17) captures the case where both firms succeed in both projects but each firm wins only one patent (with probability $\frac{p_i q_i p_j q_j}{2}$). Then, under patent, neither firm can make any profit as each firm can *hold up* the other. Under secrecy, however, both firms can compete and each can earn the profit of v. Therefore, compared with secrecy, the possibility of the hold-up effect under the patent system reduces marginal returns to investment again.

If licensing or non-assertion agreement is allowed, the hold-up effect decreases. However, as shown in the appendix, it does not disappear, and the qualitative results do not change.

Proposition 2 shows that the hold-up effects dominate the profit dissipation effect. Therefore, if firms can already protect their innovations from imitation by secrecy, an introduction of (or strengthening of) patent would *reduce* research investment. Intuitively, the profit dissipation effect arises when both firms succeed in both projects, while the hold-up effect can arise when a firm fails in one project (but wins the patent for the other). Because we assume the probability of failure is larger than that of success, the expected hold-up effect dominates the expected profit dissipation effect.

4.1 Imitation vs. Patent

Now suppose that in the absence of patent protection, firms can easily imitate other firms' research outcomes. This has been the typical assumption in the previous literature.

Imitation With costless imitation, if at least one firm succeeds in project A and if at least one firm succeeds in project B, both firms can use the two innovations and compete in the product market. Therefore, the expected profit of firm i with possible imitation (with a slight abuse of notation, denoted by π_i^M) is as follows:

$$\pi_i^M = (p_i + p_j - p_i p_j)\,(q_i + q_j - q_i q_j)\,v - I_A^i - I_B^i \tag{18}$$

where $p_i = p(I_A^i)$ and $q_i = q(I_B^i)$.

From the first order conditions and symmetry, the market equilibrium under imitation (denoted by I_A^M and I_B^M) is determined as follows:

$$\frac{\partial \pi_i^M}{\partial I_A^i} = p_i'(1 - p_j)(q_i + q_j - q_i q_j)v - 1 = 0 \tag{19}$$

$$\frac{\partial \pi_i^M}{\partial I_B^i} = (p_i + p_j - p_i p_j)q_i'(1 - q_j)v - 1 = 0 \tag{20}$$

where $p_i' = p'(I_A^M)$ and $q_i' = q'(I_B^M)$.

Imitation vs. Patent Now consider how the market equilibrium changes when patent protection is introduced.

Proposition 3 *When firms cannot rely on secrecy, patent protection increases research investment. That is,* $I_A^P > I_A^M$ *and* $I_B^P > I_B^M$.

Proof. See appendix. ■

To gain intuition, let us compare the marginal returns to investment under patent and under imitation. It turns out that it is easier to interpret if I use the marginal returns to investment under secrecy as a benchmark as follows:

$$\frac{\partial \pi_i^P(I_A^M, I_B^M)}{\partial I_A^i} - \frac{\partial \pi_i^M(I_A^M, I_B^M)}{\partial I_A^i} = \left[\frac{\partial \pi_i^P(I_A^M, I_B^M)}{\partial I_A^i} - \frac{\partial \pi_i^S(I_A^M, I_B^M)}{\partial I_A^i}\right] + \left[\frac{\partial \pi_i^S(I_A^M, I_B^M)}{\partial I_A^i} - \frac{\partial \pi_i^M(I_A^M, I_B^M)}{\partial I_A^i}\right] \tag{21}$$

From proposition 2, the first bracket captures the effect of offensive exclusion, and is negative. The second term captures the effect of defensive exclusion, and can be further decomposed into three effects as follows.

$$\frac{\partial \pi_i^S(I_A^M, I_B^M)}{\partial I_A^i} - \frac{\partial \pi_i^M(I_A^M, I_B^M)}{\partial I_A^i} = \left[p_i' q_i (1 - p_j q_j)(V - v)\right] + \left[p_i' p_j (q_i + q_j - q_i q_j) v\right] - \left[p_i' (1 - q_i) q_j v\right] > 0 \tag{22}$$

First, if firm i succeeds in both projects but firm j fails in at least one project (with probability $p_i q_i (1 - p_j q_j)$), firm i would make profit V under secrecy. However, under imitation, firm j would imitate and compete. Thus, firm i makes only v under imitation. In other words, as in the single patent race case, the defensive exclusivity of secrecy (and patent) prevents *imitation by others,* and increases marginal returns to investment.

Second, under imitation, even if firm i fails in project A, it can free-ride on firm $j's$ success in project A, especially when either firm succeeds in project B (with probability $(1 - p_i) p_j (q_i + q_j - q_i q_j)$). Under patent protection, however, firm j will win the patent for project A, and firm i will not be able to imitate it. Because patent essentially makes firm i commit not to *free-ride* on firm

$j's$ success, firm i has a larger incentive to invest in its own research under patent. Recall that these two effects are at work in the single patent race as well.

Third, under imitation, if firm i succeeds in project A, but fails in project B, firm i can still make profit v by imitating firm $j's$ successful outcome of project B (with probability $p_i(1-q_i)q_j$). I call this a *spillover* effect. Because patent does not allow this, patent decreases marginal returns to investment[9].

In a symmetric equilibrium, the first effect always dominates the third (negative) effect, because $v < \frac{V}{2}$ and $p < 1$. In other words, the positive effect of preventing imitation dominates the negative effect of not being able to imitate a complementary project.

Therefore, in an R&D portfolio race, patent provides negative incentives on investment due to offensive exclusion, but positive incentives due to defensive exclusion. Proposition 3 shows that the effect of defensive exclusion dominates that of offensive exclusion. Thus, when compared with imitation, patent protection does induce more investment.

5 Welfare Analysis

The previous section shows how the amount of R&D investment changes with the introduction of patent protection. In this section, I study the welfare effects of patent protection. Given that licensing or transfer of technology is not feasible, the expected social surplus is as follows:

$$S_{SB} = (p_1q_1 + p_2q_2 - p_1q_1p_2q_2)V - I_A^1 - I_B^1 - I_A^2 - I_B^2 \tag{23}$$

When at least one of two firms succeeds in both projects, society can get V from the complementarity of the two projects. To distinguish from the first-best case where transfer of technology is possible (see the appendix for this case), I denote this second-best social welfare by S_{SB}. Also denote the second-best investment levels by I_A^{SB} and I_B^{SB}.

[9]Careful readers will note that the spillover effects are due to a somewhat unfair comparison. Under patent, the model did not allow licensing. Under imitation, the model effectively allows technology transfer via imitation. Note however that even without the spillover effect, the marginal returns of investment under patent are larger than those under imitation. Thus, the qualitative results hold even without the spillover effect.

5.1 Market Bias of Patent Protection

Unlike the single patent race, the following proposition shows that in the patent portfolio race, the market under-invests in R&D.

Proposition 4 *Suppose that both projects can be patented. Then, firms under-invest in both project A and B. That is,* $I_A^P < I_A^{SB}$ *and* $I_B^P < I_B^{SB}$.

Proof. See appendix. ■

For the intuition, consider the market bias for project A under patent protection. As before, I compare the local difference in marginal returns to investment between the social optimum and market equilibrium as follows:

$$\frac{\partial \pi_i^P(I_A^{SB}, I_B^{SB})}{\partial I_A^i} - \frac{\partial S_{SB}(I_A^{SB}, I_B^{SB})}{\partial I_A^i} = \left[\frac{p_i' p_j}{2}\frac{q_i q_j}{2}V\right] - \left[\frac{p_i' p_j}{2} q_i(1-q_j)V\right] - \left[p_i'(1-p_j)\frac{q_i q_j}{2}V\right] \quad (24)$$

The first term captures the well-known *business-stealing effect.* If firm i wins the patent for both projects, then even when firm j succeeds in both projects as well (with probability $\frac{p_i p_j}{2}\frac{q_i q_j}{2}$) , firm j cannot gain any profits. Because firm i does not care about this negative externality, this business stealing effect leads to over-investment in project A.

The second and third terms capture the hold-up effect. For example, suppose that firm i succeeds in both projects but that firm j succeeds only in project A. Then, in the social optimum, society can enjoy the complementarity of the two projects because firm i succeeded in both projects. However, in the market equilibrium, if firm j wins the patent for project A (with probability $\frac{p_i p_j}{2} q_i(1-q_j)$) , firm i cannot make any profit. In other words, firm $j's$ patent for project A can *hold up* firm i, preventing it from appropriating from the complementarity. This hold-up effect leads to under-investment in project A.

Note that the business stealing effect arises when both firms succeed in all the projects. Since the probabilities of success in innovations are relatively small (i.e. $p < \frac{1}{2}$ and $q < \frac{1}{2}$), proposition 4 shows that the expected business stealing effect is smaller than the sum of the two hold-up effects. Thus, firms under-invest in both projects despite patent protection.

5.2 Welfare Effect of Patent Protection

Secrecy to Patent Suppose that firms can protect their innovations from imitation by secrecy.

Proposition 5 *Suppose that firms can rely on secrecy. Then,* $I_A^S \geq I_A^{SB} > I_A^P$ *and* $I_B^S \geq I_B^{SB} > I_B^P$*, where the equalities hold if* $v = 0$*. Thus, if* v *is small enough, patent protection decreases social welfare.*

Proof. See appendix. ■

First, note that contrary to the patent protection case above, under secrecy without patents, firms over-invest in R&D. For the intuition, let us compare the local difference in marginal returns to investment between the social optimum and market equilibrium under secrecy as follows:

$$\frac{\partial \pi_i^S(I_A, I_B)}{\partial I_A^i} - \frac{\partial S_{SB}(I_A, I_B)}{\partial I_A^i} = p_i' q_i p_j q_j v \geq 0 \tag{25}$$

Suppose that firm j has succeeded in both projects (with probability $p_j q_j$). Under secrecy, firm i can still make some profit v if it also succeeds in both projects. However, from the social point of view, firm $i's$ additional success is redundant. Therefore, the marginal returns under secrecy are larger than those at a social optimum.

Since firms over-invest under secrecy, but under-invest under patent, the general welfare effect of patent protection is somewhat ambiguous. However, if v is small enough (or if the profit dissipation effect is large, as in Bertrand competition), the welfare loss from over-investment under secrecy will be relatively smaller than the welfare loss from under-investment under patent. In this case, patent protection would *reduce* social welfare.

It is interesting to note that when firms can rely on secrecy, patent protection can reduce social welfare regardless of whether firms compete for a single patent or a portfolio of complementary patents, but for different reasons. When firms compete in a single patent race (or multiple independent patent races), patent protection reduces social welfare because it exacerbates the *over*investment problem (see proposition 1). However, when firms compete in a patent portfolio race, patent protection can reduce social welfare because it can lead to the *under*-investment problem.

Imitation to Patent Now suppose that firms cannot rely on secrecy. Thus, innovations can be easily imitated in the absence of patent protection.

Proposition 6 *$I_A^{SB} > I_A^P > I_A^M$ and $I_B^{SB} > I_B^P > I_B^M$. Thus, if firms cannot rely on secrecy, patent protection increases social welfare.*

Proof. From Proposition 3 and 4. ■

Not surprisingly, with imitation, firms under-invest in R&D. As shown above, patent protection increases R&D investment but not too much. Thus, patents increase social welfare.

It is worth stressing that despite the hold-up effects, patents still increase R&D investment and social welfare if firms cannot rely on secrecy or lead-time. There have been growing concerns that when firms compete for multiple patents or a 'patent thicket', the hold-up effect of patent would slow down innovations. However, it has not been clear whether the negative effect of the hold-up effect would dominate the positive effect of patents such as the prevention of the free-rider problem. Proposition 6 shows that when imitation is easy in the absence of patent protection, the positive effect of patents dominates, and increases both R&D investment and social welfare. Note the contrast with the case when firms can rely on secrecy (proposition 5), which provides a challenge to policy-makers, as we discuss below.

6 Discussion

6.1 The Patent Paradox

With stronger patent protection since 1982, the patent propensity (= # of patent applications/R&D investment) has clearly increased mostly (and paradoxically) in those industries where firms rely on secrecy and lead-time most rather than patents (e.g. semiconductor or software). Also, in industries that heavily rely on patents (e.g. pharmaceutical), no significant change in patent propensity has been observed. This is called the 'patent paradox'.[10]

[10] See Kortum and Lerner (1997), Hall and Ziedonis (2000), and Bessen (2004) for more details.

This paper provides an explanation for this empirical paradox. From lemma 1 and proposition 2, in industries that are already protected by secrecy or lead-time and where firms compete for multiple complementary innovations, stronger patent laws would induce more patent applications as *defensive patenting*, but reduce overall research investment through *hold-up effects* as discussed above. These changes would lead to a higher patent propensity. These results are also consistent with the empirical findings by Hall and Ziedonis (2000), and Bessen and Hunt (2004).

Also, from proposition 3, when firms cannot rely on secrecy and suffer from imitation, the stronger patent protection may increase research investment as well as patent applications. This result explains why the patent propensity has not changed much in those industries that regard patents as an important appropriation tool.

Previous studies have explained only a part of these puzzles. For example, Parchomovsky and Wagner (2005) explains why the patent portfolio race has increased patent applications, but does not explain why research expenditure has not increased at the same time. Shapiro (2001) and Bessen and Maskin (2006) emphasize the hold-up effects and explain why R&D expenditure may decrease when projects are complementary. However, they do not explain why different industries have responded differently to stronger patent protection[11].

6.2 The Summary and Policy Implications

This paper shows that depending on whether innovations are complementary *and* whether firms can rely on secrecy, the effects of patents on the level of investment and social welfare are very different. Table 1 summarizes these results.

Table 1 Effect of Patent and Optimal Policy

(when firms can fully appropriate the social value of innovations)

[11] One alternative explanation is that innovations in these other industries, such as the pharmaceutical industry, are not complementary or cumulative, though it does not seem obvious.

Innovations	Independent		Complementary	
Comparison	$I^P > I^S \geq I^* > I^M$		$I^S \geq I^* > I^P > I^M$	
Secrecy	yes	no	yes	no
Effect of Patent	$I \Uparrow$, $SW \Downarrow$	$I \Uparrow$, SW ?	$I \Downarrow$, SW ?	$I \Uparrow$, $SW \Uparrow$
Optimal Policy	no patent	weak patent	weak patent	strong patent

(note: I^P = investment under patent; I^S = investment under secrecy; I^* = socially optimal investment level; I^M = investment under imitation)

Suppose firms in an industry are largely competing for a single or independent innovations. (i) If firms can use secrecy to protection their innovations, firms will over-invest in innovations even without patent protection. Since the patent will increase investment even more, *no patent protection* is desirable in such an industry. (ii) However, if firms cannot use secrecy, firms will under-invest in innovations. Even though patents increase investment, strong patents can increase investment too much. Therefore, a *weak patent protection* (to *increase* investment but not too much) will be optimal in this case.

Now suppose that firms in an industry are largely competing for multiple complementary innovations. Industries with technologically complex products would be such an example. (iii) If firms can use secrecy to protect their innovations, they tend to over-invest in innovations. As shown above, patent protection in this case reduces investment, and strong patent protection leads to under-investment. Therefore, *a weak patent protection* (to *decrease* investment slightly) is optimal in this case. (iv) If firms cannot use secrecy, firms will under-invest in innovations. In this case, patent increases investment, and we have no concerns about over-investment. Therefore, *strong patent protection* (to *increase* investment) is required in this case.

Note that if firms cannot rely on secrecy, as most previous studies have assumed, the effect of patent is quite similar *regardless* of whether firms are competing for a single innovation or multiple complementary innovations (or an R&D portfolio). The patent will increase market investment and increase social welfare, as long as the patent does not lead to too much over-investment.

Therefore, it is only when firms can rely on secrecy that a policy maker should consider the potentially negative effect of patents on investment and social welfare depending on whether firms compete for a single innovation or an R&D portfolio. On the other hand, firms are increasingly relying on secrecy, and their products are becoming more technologically complex. Therefore, the negative effect of patent protection on investment and social welfare through hold-up effects should be taken more seriously.

As usual, these policy implications should be interpreted with caution. For example, throughout the paper, I have assumed that a monopolist can fully appropriate the social value of innovation. However, if even a monopolist cannot fully appropriate the social returns of innovation (i.e. $V < V^S$ where V^S is the social value of innovations), firms may under-invest in R&D regardless of patent or secrecy. Table 2 describes policy implications in such a case.

Table 2 Effect of Patent and Optimal Policy

(when firms can *not* fully appropriate the social value of innovations)

Innovations	Independent		Complementary	
Comparison	$I^* > I^P > I^S > I^M$		$I^* > I^S > I^P > I^M$	
Secrecy	yes	no	yes	no
Effect of Patent	$I \Uparrow$, $SW \Uparrow$	$I \Uparrow$, $SW \Uparrow$	$I \Downarrow$, $SW \Downarrow$	$I \Uparrow$, $SW \Uparrow$
Optimal Policy	strong patent	strong patent	no patent	strong patent

(note: I^P = investment under patent; I^S = investment under secrecy; I^* = socially optimal investment level; I^M = investment under imitation)

Two general implications emerge from Table 1 and 2, regardless of whether firms can fully appropriate the social returns of innovations or not. First, if firms cannot rely on secrecy (or lead-time), some degree of patent protection increases R&D investment and social welfare, regardless of whether firms compete for a single patent or a patent portfolio. Second, if firms compete for a patent portfolio and if they can rely on secrecy, patent protection reduces R&D investment and possibly social welfare too. These results are particularly important given the recent debate on whether strong patents can slow down innovations due to the hold-up effect.

These results present a challenge to a patent policy maker, because a patent policy suited for one industry will not be optimal for other industries. Even though a product or industry-specific patent policy may be difficult to implement, other policy instruments such as subsidy or government-owned research centers can be more industry-specific. The optimal policy combination of patent and these other policy instruments would be an interesting topic for future research.

References

[1] Anton, J. and D. Yao, (2004). "Little Patents and Big Secrets: Managing Intellectual Property," *Rand Journal of Economics*, 35 (1), 1-22

[2] Bessen, J. (2004). "Hold-up and Patent Licensing of Cumulative Innovations with Private Information," *Economics Letters*, 82 (3), 321-326

[3] Bessen, J. and R. M. Hunt, (2004). "An Empirical Look at Software Patents," Federal Reserve Bank Philadelphia Working paper No.03-17/R

[4] Bessen, J. and E. Maskin (2006). "Sequential Innovations, Patent and Imitation," *mimeo*

[5] Cabral, L. (1994). "Bias in market R&D portfolios," *International Journal of Industrial Organization*, 12, pp. 533-547

[6] Cohen, W., R. Nelson, and J. Walsh (2000). "Protecting Their Intellectual Assets: Appropriability Conditions and Why U.S. Manufacturing Firms Patent (or Not)," NBER working paper W7552.

[7] Dasgupta, P. and Maskin, E. (1987). "The simple economics and research portfolios," *The Economic Journal*, 97, pp. 581-595

[8] Denicolo', V. and L.A. Franzoni (2004). "Patents, Secrets, and the First-Inventor Defense," *Journal of Economics and Management Strategy*, 13 (3), pp. 517-538

[9] Hall, B. and R.H. Ziedonis (2000). "The Patent Paradox Revisited: An Empirical Study of Patenting in the US Semiconductor Industry, 1979-95" mimeo

[10] Kortum, S. and J. Lerner, (1998). "Stronger Protection or Technological Revolution: What is Behind the Recent Surge in Patenting", Carnegie-Rochester Conferece Series on Public Policy, 48, 247-304

[11] Lee, T.K. and Wilde, L.L. (1980). "Market Structure and Innovation: A Reformulation," *Quarterly Journal of Economics*, 94, pp. 429-436

[12] Levin, R.C., A. Klevorick, R.R. Nelson, and S.G. Winter (1987). "Appropriating the Returns from Industrial Research and Development," *Brookings Papers on Economic Activity*, 3, 783-820

[13] Loury, G. (1979). "Market Structure and Innovation," *Quarterly Journal of Economics*, 93, pp. 395-410

[14] Mansfield, E., (1986). "Patents and Innovation: An Empirical Study," Management Science, 32, pp. 173-181

[15] Mansfield, E., M. Schwartz, and S. Wagner (1981). "Imitation Costs and Patents: An empirical study," *Economic Journal*, 91. pp.907

[16] O'Donoghue, T., S. Scotchmer, and J. Thisse, (1998). "Patent Breadth, Patent Life and the Pace of Technological Progress," *Journal of Economics and Management Strategy*, 7, 1-32

[17] Parchomovsky, G, and R. P. Wagner (2005). "Patent Portfolios," *U of Penn. Law School, Public Law Working Paper 56*

[18] Scotchmer, S. (1991). "Standing on the Shoulders of Giants: Cumulative Research and the Patent Law," *Journal of Economic Perspectives*, 5. 29-41

[19] Scotchmer, S., and J. Green (1990). "Novelty and Disclosure in Patent Law," *Rand Journal of Economics*, 21 (1), pp. 131-146

[20] Shapiro, C. (2001). "Navigating the Patent Thicket: Cross Licenses, Patent Pools, and Standard-Setting," *Innovation Policy and the Economy*, Volume 1, A. Jaffe, J. Lerner, and S. Stern eds., MIT Press

Appendix A Non-Assertion Agreement and Licensing Agreement

Non-Assertion Agreement The hold-up effect with patents arises when one firm has succeeded in both projects but the other firm wins the patent for one of the two projects. As in the BlackBerry patent dispute case (see footnote 4), firms often settle on a non-assertion agreement in this case. That is, the firm with a blocking patent agrees not to assert its patent in exchange for monetary compensation. Note that a non-assertion agreement differs from licensing as it does not require the transfer of technology.

Assuming a Nash bargaining solution, firm $i's$ expected profit under patent with a non-assertion agreement (denoted by π_i^{PN}) is as follows:

$$\begin{aligned} \pi_i^{PN} &= p_i(1-\frac{p_j}{2})q_i(1-\frac{q_j}{2})V + p_i(1-p_j)\frac{q_iq_j}{2}\frac{V}{2} + \frac{p_ip_j}{2}q_i(1-q_j)\frac{V}{2} \\ &\quad + p_j(1-p_i)\frac{q_iq_j}{2}\frac{V}{2} + \frac{p_ip_j}{2}q_j(1-q_i)\frac{V}{2} + \frac{p_ip_jq_iq_j}{2}\frac{V}{2} - I_A^i - I_B^i \end{aligned} \tag{A.1}$$

Note that if firm i wins the patent for project A and succeeds in project B, but firm j wins the patent for project B (with probability $p_i(1-p_j)\frac{q_iq_j}{2}$) , firm i can now earn $\frac{V}{2}$ through a non-assertion agreement. Also firm i can get revenue $\frac{V}{2}$ from the non-assertion agreement, if it holds a blocking patent.

From (11) and (A.1), in a symmetric equilibrium, the difference between marginal returns to investment under patent and under secrecy is now as follows:

$$\frac{\partial \pi_i^{PN}}{\partial I_A^i} - \frac{\partial \pi_i^{S}}{\partial I_A^i} = -p_i'q_i(\frac{q_j}{4}(1-2p_j) + vp_jq_j) < 0 \tag{A.2}$$

The inequality is due to $p < \frac{1}{2}$ from the assumption. Therefore, even with a non-assertion agreement, patent protection will reduce R&D investment if firms can rely on secrecy.

Also, the difference between marginal returns to investment under patent and under social optimum is now as follows:

$$\frac{\partial \pi_i^{PN}}{\partial I_A^i} - \frac{\partial S_{SB}}{\partial I_A^i} = -\frac{1}{4}Vp_i'q_iq_j(1-2p_j) < 0 \tag{A.3}$$

Therefore, even with a non-assertion agreement, firms invest less under patent than at social optimum. Then, from proposition 5, if v is small enough, patent protection reduces social welfare when firms can rely on secrecy.

Licensing Now suppose that licensing is feasible under the patent scheme. Licensing will occur only when one firm wins the patent for project B and the other firm wins the patent for project A. In such a case, assuming a Nash bargaining solution, each firm will receive $\frac{V}{2}$. Then, firm $i's$ expected profit with licensing (denoted by π_i^{LP}) is as follows:

$$\begin{aligned}\pi_i^{LP} &= p_i(1-\frac{p_j}{2})q_i(1-\frac{q_j}{2})V + p_i(1-\frac{p_j}{2})q_j(1-\frac{q_i}{2})\frac{V}{2} \\ &\quad + p_j(1-\frac{p_i}{2})q_i(1-\frac{q_j}{2})\frac{V}{2} - I_A^i - I_B^i \qquad \text{(A.4)}\end{aligned}$$

Let us denote the market equilibrium under patent with licensing by I_A^{LP} and I_B^{LP}.

Similarly, consider the expected profit when firms can keep their research outcomes secret. Under secrecy, the expected profit with licensing is as follows:

$$\begin{aligned}\pi_i^{LS} &= p_iq_i(1-p_jq_j)V + p_iq_ip_jq_jv \qquad \text{(A.5)} \\ &\quad + (1-p_i)q_ip_j(1-q_j)\frac{V}{2} + p_i(1-q_i)(1-p_j)q_j\frac{V}{2} - I_A^i - I_B^i\end{aligned}$$

Also denote the market equilibrium under secrecy with licensing by I_A^{LS} and I_B^{LS}. Note that unlike patent protection, licensing will take place if one firm succeeds in project A only and if the other firm succeed in project B only.

From (A.4) and (A.5), it is straightforward to show that the marginal returns to investment under patent are still smaller than those under secrecy as follows:

$$\frac{\partial \pi_i^{LP}(I_A^{LS}, I_B^{LS})}{\partial I_A^i} - \frac{\partial \pi_i^{LS}(I_A^{LS}, I_B^{LS})}{\partial I_A^i} = -\frac{1}{4}Vp_i'q_iq_j(1-2p_j) - vp_jq_iq_jp_i' < 0 \qquad \text{(A.6)}$$

To compare with the social optimum, I first need to re-define the social optimum because I am now allowing for transfer of technology or information sharing. The expected social optimum with information sharing, called the first-best social optimum, is as follows:

$$S_{FB} = (p_1+p_2-p_1p_2)(q_1+q_2-q_1q_2)V - I_A^1 - I_B^1 - I_A^2 - I_B^2 \qquad \text{(A.7)}$$

Note that if at least one firm succeeds in project A and if at least one firm succeeds in project B, society can enjoy the value V through possible information sharing.

In comparison with the first-best social optimum, the marginal returns to investment under patent (with licensing) are still smaller than those at the social optimum as follows:

$$\frac{\partial \pi_i^{LP}(I_A^{FB}, I_B^{FB})}{\partial I_A^i} - \frac{\partial S_{FB}(I_A^{FB}, I_B^{FB})}{\partial I_A^i} = -\frac{V}{4}p'q(1-2p)(2-q) < 0 \tag{A.8}$$

The subscripts are omitted due to symmetry. Therefore, even with licensing, firms invest less than the socially optimal amount.

The marginal returns of investment under secrecy (with licensing) are also smaller than those at the social optimum if v is small enough, as shown below:

$$\frac{\partial \pi_i^{LS}(I_A^{FB}, I_B^{FB})}{\partial I_A^i} - \frac{\partial S_{FB}(I_A^{FB}, I_B^{FB})}{\partial I_A^i} = \frac{1}{2}p'q\left(-V\left(1-2p\right)\left(1-q\right) + 2pqv\right) \tag{A.9}$$

Recall that without licensing, compared with the second-best social optimum, firms over-invest under secrecy. However, if licensing is feasible, then firms under-invest compared with the first-best social optimum.

However, the welfare effect of patent does not change. That is, when firms can rely on secrecy, patent protection reduces social welfare as it exacerbates the under-investment problem.

Appendix B Proof of Propositions

Proof of Proposition 1 With a slight abuse of notation, let us denote $S(I_A^*, I_A^*)$ simply by $S(I_A^*)$. The same simplification of notation applies to the other profit functions. Then, from (2) and (10),

$$\frac{\partial \pi_i^M}{\partial I_A^i}(I_A^*) - \frac{\partial S}{\partial I_A^i}(I_A^*) = -p'(I_A^*)(1-p(I_A^*))(V_A - v_A) < 0 \tag{A.10}$$

Since $\frac{\partial \pi_i^M}{\partial I_A^i}$ is decreasing, $I_A^* > I_A^M$.

From (4) and (10),

$$\frac{\partial \pi_i^S}{\partial I_A^i}(I_A^*) - \frac{\partial S}{\partial I_A^i}(I_A^*) = p'(I_A^*)p(I_A^*)v_A > 0 \tag{A.11}$$

Since $\frac{\partial \pi_i^S}{\partial I_A^i}$ is decreasing from the second order condition, $I_A^S > I_A^*$.

From equation (8), $I_A^P > I_A^S$. Therefore, $I_A^P > I_A^S > I_A^* > I_A^M$.

Since we assume there is no deadweight loss in the market equilibrium, social welfare in different symmetric market equilibria is entirely determined by the amount of research investment (I). Given the assumption that social welfare function is globally concave, the (symmetric) market equilibrium under patent is farther away from the social optimum than the market equilibrium under secrecy. Therefore, we must have $S(I_A^*) > S(I_A^S) > S(I_A^P)$.■

Proof of Proposition 2 The equation (17) can be simplified as follows:

$$\frac{\partial \pi_i^P(I_A^S, I_B^S)}{\partial I_A^i} - \frac{\partial \pi_i^S(I_A^S, I_B^S)}{\partial I_A^i} = p_i' q_i \left[-p_j(\frac{1}{2} - \frac{5}{8}q_j)V - q_j(\frac{1}{2} - \frac{5}{8}p_j)V - vp_j q_j \right] < 0 \qquad \text{(A.12)}$$

The inequality is due to $p < \frac{1}{2}$ and $q < \frac{1}{2}$. Similarly, $\frac{\partial \pi_i^P(I_A^S, I_B^S)}{\partial I_B^i} - \frac{\partial \pi_i^S(I_A^S, I_B^S)}{\partial I_B^i} < 0$.

It is simpler to prove this using graphs. With a slight abuse of notation, when $I_A^1 = I_A^2 = I_A$ and $I_B^1 = I_B^2 = I_B$, define $\pi_i^P(I_A, I_B) = \pi_i^P(I_A^1, I_B^1, I_A^2, I_B^2)$. The same notation applies to the other profit functions.

First, note that the implicit functions $\frac{\partial \pi_i^P(I_A, I_B)}{\partial I_A^i} = 0$ and $\frac{\partial \pi_i^P(I_A, I_B)}{\partial I_B^i} = 0$ have positive slopes in the (I_A, I_B) coordinate from $p'' < 0$ and $q'' < 0$. Also, $\frac{\partial \pi_i^P(I_A^P, I_B^P)}{\partial I_B^i} = 0$ has a steeper slope than $\frac{\partial \pi_i^P(I_A, I_B)}{\partial I_A^i} = 0$ as shown in figure A.1 from the second order condition. Similarly, $\frac{\partial \pi_i^S(I_A, I_B)}{\partial I_A^i} = 0$ and $\frac{\partial \pi_i^S(I_A, I_B)}{\partial I_B^i} = 0$ have positive slopes in the (I_A, I_B) coordinate, and $\frac{\partial \pi_i^S(I_A^P, I_B^P)}{\partial I_B^i} = 0$ has a steeper slope than $\frac{\partial \pi_i^S(I_A, I_B)}{\partial I_A^i} = 0$.

[Figure A.1 here]

From (A.12), $\frac{\partial \pi_i^P(I_A, I_B)}{\partial I_A^i} = 0$ must be below $\frac{\partial \pi_i^S(I_A, I_B)}{\partial I_A^i} = 0$. Similarly, $\frac{\partial \pi_i^P(I_A, I_B)}{\partial I_B^i} = 0$ must be to the left of $\frac{\partial \pi_i^S(I_A, I_B)}{\partial I_B^i} = 0$ as shown in figure A.1. Therefore, $I_A^P < I_A^S$ and $I_B^P < I_B^S$.■

Proof of Proposition 3 The equation (21) can be simplified as follows:

$$\frac{\partial \pi_i^P(I_A^M, I_B^M)}{\partial I_A^i} - \frac{\partial \pi_i^M(I_A^M, I_B^M)}{\partial I_A^i} = \frac{1}{2} p_j q_j p_i'(1 - \frac{1}{2} q_i)V + p_i'(1 - p_j)(q_i + q_j - q_i q_j)(\frac{V}{2} - v) > 0 \quad \text{(A.13)}$$

The inequality follows from $v < \frac{V}{2}$. Similarly, $\frac{\partial \pi_i^P(I_A^M, I_B^M)}{\partial I_B^i} - \frac{\partial \pi_i^M(I_A^M, I_B^M)}{\partial I_B^i} > 0$.

The rest of the proof is almost identical to the proof of proposition 2, and omitted.■

Proof of Proposition 4 The proof is essentially identical to the proof of proposition 2. Thus, I only show that $\frac{\partial \pi_i^P(I_A, I_B)}{\partial I_A^i} - \frac{\partial S_{SB}(I_A, I_B)}{\partial I_A^i} < 0$ for all (I_A, I_B). From (24),

$$\frac{\partial \pi_i^P(I_A^{SB}, I_B^{SB})}{\partial I_A^i} - \frac{\partial S_{SB}(I_A^{SB}, I_B^{SB})}{\partial I_A^i} = -p_i' q_i \left(q_j(\frac{1}{2} - p_j) + p_j(\frac{1}{2} - q_j) + \frac{3}{4} p_j q_j \right) V < 0 \quad \text{(A.14)}$$

The inequality follows from assumption 1.■

Proof of Proposition 5 From proposition 4, $I_k^P < I_k^{SB}$. $(k = A, B)$. From (24), $\frac{\partial \pi_i^S(I_A, I_B)}{\partial I_A^i} - \frac{\partial S_{SB}(I_A, I_B)}{\partial I_A^i} \geq 0$ for all (I_A, I_B).The rest of the proof is almost identical to the proof of proposition 2. Thus, $I_k^S \geq I_k^{SB}$. Also note that if $v = 0$, then from (24), $\frac{\partial \pi_i^S(I_A, I_B)}{\partial I_A^i} - \frac{\partial S_{SB}(I_A, I_B)}{\partial I_A^i} = 0$. Therefore, if $v = 0$, then $I_k^S = I_k^{SB}$. $(k = A, B)$■

Figure A.1 Secrecy to Patent