Aoki, Reiko; Spiegel, Yossi

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Pre-Grant Patent Publication and Cumulative Innovation*

By

Reiko Aoki†
University of Auckland

and

Yossi Spiegel‡
Tel Aviv University

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† Department of Economics, University of Auckland, email: r.aoki@auckland.ac.nz.

‡ Recanati Graduate School of Business Administration, Tel Aviv University, Ramat Aviv, Tel Aviv 69978, Israel. email: spiegel@post.tau.ac.il. http://www.tau.ac.il/~spiegel/

Abstract

We examine the implications of pre-grant publication (PP) of patent applications in the context of a cumulative innovation model. We show that pre-grant publication of patents lead to fewer applications and fewer inventions, but it raises the probability that new technologies will reach the product market and thereby enhances consumer surplus and possibly welfare as well.

JEL Classification: O34 O31

Keywords: R&D, patents, patent systems, pre-grant patent publication, patenting decision, spillover, consumer surplus, welfare

1 Introduction

The two main objectives of patent systems are to encourage investments in R&D by granting inventors a temporary monopoly over the use of their inventions and to facilitate the dissemination of R&D knowledge. One aspect of patent systems that reflects the desire to balance these conflicting objectives is the requirement to publicly disclose pre-grant patent applications after 18 months from the date of application. This requirement, which is place in practically every industrialized country (see Ragusa 1992), implies that inventors may face the risk that their knowledge will be made public even if eventually their patent applications are rejected. Not surprisingly, opponents of this requirement argue that this risk may discourage innovations, especially by small independent inventors who lack the means to vigorously protect their intellectual property. A notable exception to the 18 months rule is the current U.S. patent system which allows applicants to keep their patent applications confidential until an actual patent is issued, provided that they do not seek patent protection in another country in which the 18 months rule applies.[1]

In this paper we examine the implications of pre-grant publication of patent applications in the context of a cumulative innovation model. In this model, two firms engage in an R&D process aimed at developing a new commercial technology. The R&D process consists of two (cumulative) phases. In the first phase, the two firms accumulate interim R&D knowledge.[2] This phase ends when one firm manages to accumulate enough interim R&D knowledge to file for a patent. Given the leading firm's decision on whether or not to file for a patent, the two firms choose how much to invest in the second phase of the R&D process. These investments in turn determine the likelihood that each firm will successfully

[1] Until the passage of the American Inventors Protection Act (AIPA) in 1999, patent applications in the U.S. were kept confidential until a patent was actually granted. Since 1999, approximately 10% of all applicants opt-out of publication (FTC, 2005, p. 11). The Patent Reform Act (HR.2795 introduced in June 2005 and S.3818 introduced in August 2006) and the Patents Depend on Quality Act (H.R. 5096 introduced in April 2006), propose to eliminate the exemptions from the 18 month rule and require all patent applications will be made public after 18 months.

[2] For instance, in the context of biotechnology, the interim R&D knowledge could represent a research tool like a cell line, chemical reagent, or antibody which is used in research but does not have independent value outside of research.

develop the new commercial technology at the end of the second phase.

We assume that the superior interim knowledge of the leading firm gives it a strategic advantage in the second phase of the R&D process. Some of this advantage however is lost when the leading firm files for a patent because the lagging firm gets access to the leading firm's superior knowledge either through the patent application (if it is published) or through the actual patent (if and when it is granted). On the other hand, having a patent allows the leading firm to sue the lagging firm if the latter manages to develop the new commercial technology on the grounds that this technology infringes on the leading firm's interim knowledge. Hence, in deciding whether or not to seek a patent on its interim R&D knowledge, the leading firm needs to trade off the benefit from being able to sue the lagging firm for patent infringement against the technological spillover that diminishes its technological lead.

In principle, pre-grant patent publication (PP) may have two main effects: first, it leads to a greater technological spillover because the leading firm's interim R&D knowledge is publicly disclosed for sure after 18 months rather than being disclosed only if and when a patent is granted. Second, PP may credibly reveal to the lagging firm that the leading firm is indeed leading and may also affect the lagging firm's beliefs about the extent of this lead. In this paper we focus on the first, spillover, effect of PP. This effect figures prominently in the public debate in the U.S. about PP. Moreover, to the extent that R&D investments in the second phase of the R&D process are strategic substitutes (as is the case in our model), the leading firm may wish to voluntarily disclose this fact through publications in scientific journals or presentations in scientific conferences or trade shows in order to gains a strategic advantage over the lagging firm.

To study the implications of the technological spillover effect of PP, we compare the equilibrium across two filling systems: a PP system in which the interim R&D knowledge of the leading firm is made public whenever it files for a patent, and confidential filing (CF) system in which this knowledge is made public only if and when a patent is granted. In the main part of the paper, we focus on the second phase of the R&D process and study the implications of the spillover effect of PP for the leading firm's filing decision, for the investment levels of the two firms in the second phase of the R&D process, and for consumer

surplus and social welfare. Towards the end of the paper, we return to the first phase of the R&D process and examine the implications of the spillover effect of PP for the incentives of the two firms to accumulate interim R&D knowledge.

We show that the implications of PP depend on the strength of patent protection which depends in our model on two factors: (i) the likelihood that the patent office will grant the leading firm a patent on its interim R&D knowledge, and (ii) the likelihood that the patent will be upheld in court. PP matters however only if patent protection is strong or intermediate because when patent protection is weak, the leading firm does not file for a patent under both filing systems. When patent protection is strong, the leading firm files for a patent under both filing systems, but since PP creates a technological spillover, it induces the leading firm to cut its investment in the second phase of the R&D process while inducing the lagging firm to invest more. When the cost of R&D in the second phase of the R&D process is quadratic, PP raises the overall likelihood that the new technology will reach the product market, and hence it benefits consumers. If in addition the marginal cost of investment is sufficiently large, then PP raises social welfare (measured as the sum of the expected consumers' surplus and expected profits) as well. On the other hand, since PP hurts the leading firm, it weakens the incentives to invest in the first phase of the R&D process and accumulate interim R&D knowledge.

Things are much more subtle when patent protection is intermediate. Now the leading firm files for a patent under the CF but not under the PP system, and the effect of PP on the investments in the second phase of the R&D process depend on the likelihood that a patent will be upheld in court: when this likelihood is large, PP induces the leading firm to cut its investment level while inducing the lagging firm to invest more. On the other hand, when the likelihood that a patent will be upheld in court is small, PP has an ambiguous effect on the investment levels of the two firms because the leading firm does not file for a patent under the PP system. Nonetheless, when the cost of R&D in the second phase of the R&D process is quadratic, PP still benefits consumers regardless of the likelihood that a patent will be upheld in court. And, when the marginal cost of investment is sufficiently large, PP enhances social welfare if patents are likely to be upheld in court, but it decreases social welfare otherwise. Unlike in the intermediate protection case, now PP has an ambiguous

effect on the incentives to invest in first phase of the R&D process as it hurts both firms.

The economic literature has already studied various aspects of patent laws, including the optimal length and breadth of patents (e.g., Nordhaus, 1969; Gilbert and Shapiro, 1990; Klemperer, 1990; Gallini, 1992; Chang 1995; Green and Scotchmer 1995; Matutes, Regibeau, and Rockett, 1996; Eswaran and Gallini, 1996; O'Donoghue, 1998; and O'Donoghue, Scotchmer, and Thisse, 1998), priority rules such as "first to file" versus "first to invent" (e.g., Scotchmer and Green, 1990), novelty requirements (e.g., Scotchmer and Green, 1990; Scotchmer 1996; Eswaran and Gallini, 1996; and O'Donoghue, 1998), the optimal renewal of patents (Cornelli and Schankerman, 1999), and the optimal length of protection given to the first firm to discover interim R&D knowledge (Bloch and Markowitz, 1996). However, pre-grant patent publication has received very little attention in the economic literature. Given the continuing debate in the U.S. about the 18 months rule, it seems that a formal economic analysis of this issue is badly needed.

We are aware of only two papers that examine the implication of PP. Aoki and Prusa (1996) assume that PP reveals information about the quality choice of the first filer to its rival. They show that this information allows the firms to coordinate their R&D investments and as a result, a more collusive outcome is reached. Unlike the current paper though, the decision to patent is not endogenous, filing for a patent does not create a technological spillover, and patenting does not allow the first filer to exclude its rival from the product market. Johnson and Popp (2003) examine citation analysis on all U.S. domestic patents from 1976 to 1996 and find that more "significant" patents (those that are subsequently cited more often) tend to take longer through the application process and hence are more likely to be affected by PP. Moreover, their analysis suggests that earlier disclosure should lead to faster diffusion of R&D knowledge. While faster diffusion benefits future inventors, it hurts the filing inventors and may therefore make them more reluctant to file for patents.

The rest of the paper is organized as follows: in Section 2 we describe the model and in Sections 3 and 4 we study the equilibrium under the PP and CF systems. In Section 5 we compare the two filing systems in terms of the equilibrium patenting and investment behavior of the two firms and use the results to examine the implications of PP for consumers' surplus and social welfare. In Section 6, we examine the implications of PP for the incentives

to accumulate interim R&D knowledge. We conclude in Section 7. All proofs are in the Appendix.

2 The Model

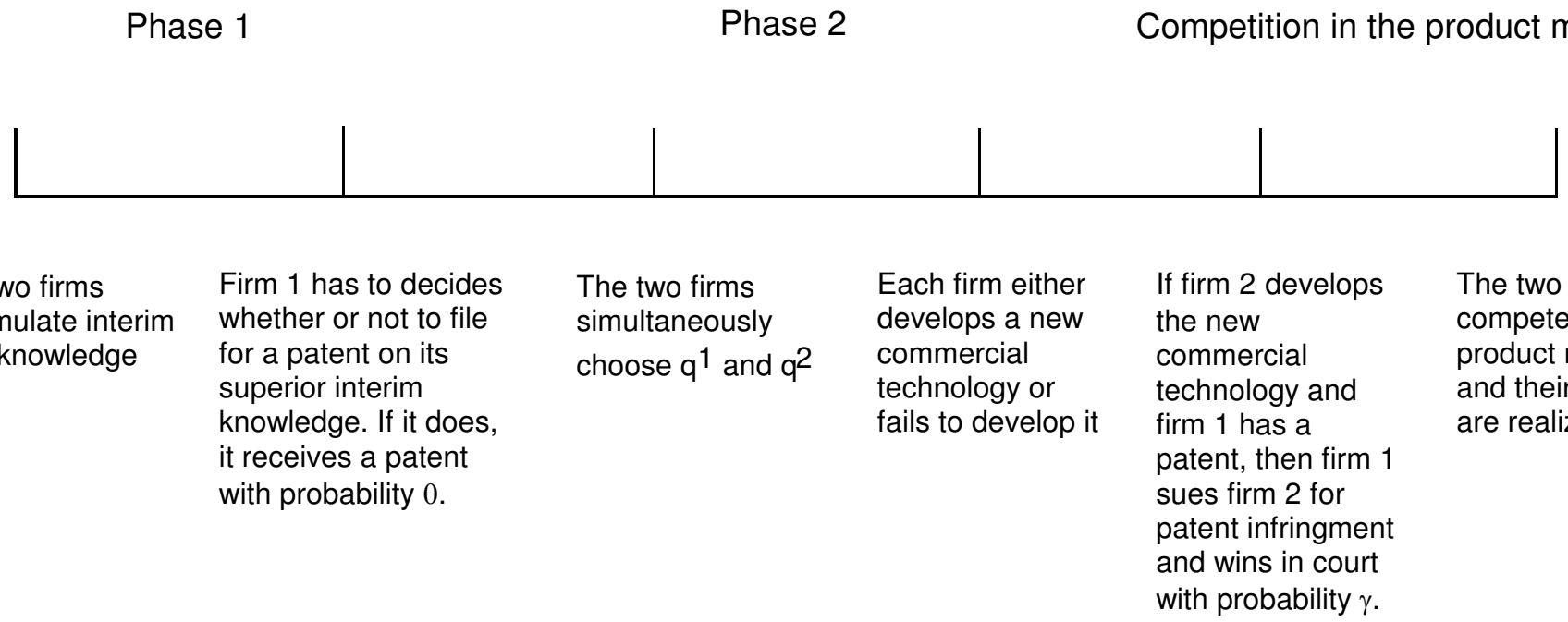
We consider two firms that engage in an R&D process aimed at developing a new commercial technology. The R&D process consists of two (cumulative) phases which are illustrated in Figure 1. In the first phase, the two firms accumulate interim R&D knowledge (e.g., a research tool or some basic technology).[3] The first phase ends when one firm (firm 1) manages to accumulate enough interim knowledge to apply for a patent. The knowledge of the rival firm (firm 2) is insufficient to apply for a patent. The superior interim knowledge of firm 1 gives it a strategic advantage in the second phase of the R&D process.[4] However, if firm 1 files for a patent then some of this advantage may be spilled over to firm 2 either through firm 1's patent application (if it is made public), or through an actual patent (if and when it is granted). The benefit from applying for a patent is that if the patent is granted, then firm 1 can sue firm 2 for patent infringement if firm 2 manages to develop the new technology at the end of the second phase.[5] Given firm 1's patenting decision, but before the patent office makes a decision, the two firms continue with their R&D in the second phase of the R&D process, and each firm either succeeds to develop the new technology or else it fails and develops nothing. Finally, the two firms compete in the product market.

[3] We will assume that the interim R&D knowldge has no commercial value of its own; this assumption however is inconsequential given that most of our analysis focuses on the second phase of the R&D process.

[4] We abstract from the possibility that firm 1 will license its superior interim knowledge to firm 2. For analysis of licensing of interim R&D knowledge, see Spiegel (2007). We also assume that if firm 1 files for a patent, it does so without delay. This assumption is motivated by the fact that in practice, there are many advantages to file for a patent as early as possible even under the first-to-invent rule used in the U.S. (see Kelly, 1995).

[5] The tradeoff that firm 1 is facing is reminiscent of the tradeoff studied by Horstman, MacDonalds, and Slivinski (1985), although the technological spillover that patenting creates in their model arises because patenting reveals to the lagging firm how profitable it would be to immitate or duplicate the leading firm. For a related tradeoff, see Erkal (2005).

Figure 1: The sequence of events in the sequential R&D game



The filing system

We consider two filling systems: a pre-grant patent publication system (PP system) and a confidential filing system (CF system). Under the PP system, the contents of patent applications are automatically published after a certain period of time from the application date (typically 18 months). Under the CF system, patent applications are kept confidential until a patent is granted, and if a patent is not granted then no information is revealed. In practice, patent protection is imperfect both because patent applications are sometimes rejected by the patent office if they are not deemed sufficiently novel, useful, or non-obvious, and because actual patents are not always upheld in court.[6] We capture these imperfections by assuming that if firm 1 applies for a patent at the end of the first phase, then it gets a patent with probability $\theta \in [0,1]$, and if firm 1 sues firm 2 for patent infringement at the end of the second phase, then it wins in court with probability $\gamma \in [0,1]$.[7] Throughout we treat θ and γ as exogenous parameters.[8]

[6] In 2003, the grant rates were 59.9% at the EPO, 49.9% at the JPO, and 64% at the USPTO (USPTO (2004) Table 4). Allison and Lemley (1998) find that out of the 300 final patent validity decisions by U.S. courts during the period 1989–1996, only 162 patents (54%) were held valid. In Japan, the original patent was upheld in only 23 out of the 51 patent infringement suits studied between April 2000 and January 2003 (45.1%) (Material prepared for 4th meeting of Subcommittee on Intllectual Property Disputes, Committee for Legal System Reform Headquarters for Promotion of Judicial Reform, Prime Minister's Office (January 31, 2003)).

[7] The assumption that patent protection is imperfect has also been made elsewhere. Meurer (1989), Anton and Yao (2003, 2004), and Choi (1999) assume that patents can be challenged in court and may be ruled as invalid, but unlike in our model, the possibility that patent applications may be rejected plays no role in these papers. Kabla (1996) assumes that patent applications may be rejected, but does not consider the possibility that patents may not be upheld in court. Waterson (1990) and Crampes and Langinier (2002) assume that suing for patent infringement is costly so patentholders do not always sue imitators. By contrast, we assume that it always pays the patentholder to sue for patent infringement. Finally, Crampes and Langinier (1998) show that under certain conditions, firms may choose not renew their patents in order to conceal favorable market information from potential entrants.

[8] According to the enablement doctrine of patent law, "claims ought to be bounded to a significant degree by what the disclosure enables, over and beyond prior art" (Merges and Nelson, 1994, p.10). Thus, in a more general model where firm 1 can choose the scope of its disclosure, the likelihood that a court will uphold firm 1's patent would be an endogenous variable.

The cost of R&D in the second phase of the R&D process

Given firm 1's filing decision, but before the patent office decides whether to grant firm 1 a patent, firms 1 and 2 simultaneously choose their investment levels in the second phase of the R&D process.[9] Instead of assuming that the two firms choose their monetary investments in R&D and that these investments determine their respective probabilities of success, q^1 and q^2, we shall assume that the two firms directly choose q^1 and q^2 and that these choices in turn determine the cost functions of the two firms. In the Appendix we illustrate how the cost functions can be derived from the probabilities of success.

We capture the strategic advantage that firm 1 enjoys in the second phase of the R&D process due to the superior interim R&D knowledge that it has accumulated in the first phase by assuming that firm 1's cost of achieving a given probability of success q is lower than that of firm 2. Specifically, we assume that firm 1's cost of investment in the second phase is $C(q)$, where $C(q)$ is twice continuously differentiable, increasing, and strictly convex, with $C'(0) = 0$. Firm 2's cost of investment depends on the degree of technological spillover, which in turn depends on whether firm 1 applies for a patent and on which filing system is in place. Whenever firm 1 applies for a patent and the PP system is in place, then firm 2 gets access to firm 1's superior interim knowledge from the patent application, regardless of whether a patent is eventually granted. Under the CF system by contrast, firm 2 gets access to firm 1's superior interim knowledge only if and when a patent is actually granted. Since the examination process of patent applications is typically much longer than 18 months (see footnote 9), there is a larger technological spillover under the PP system. Accordingly, we assume that whenever firm 1 applies for a patent, firm 2's cost of investment in the second phase of the R&D process is $\beta_L C(q)$ under the PP system, whereas under the CF system it is $\beta_M C(q)$ if a patent is eventually granted and $\beta_H C(q)$ if a patent is not granted, where $\beta_H > \beta_M > \beta_L > 1$. If firm 1 does not apply for a patent, then there is no technological spillover and firm 2's cost of investment in the second phase of the R&D process is $\beta_H C(q)$. Hence, the strategic advantage that firm 1 enjoys at the end of the first phase

[9] This timing reflects the fact that patent examination is typically a lengthy process: pendency time at USPTO was 26.7 months in 2003. Pendency times at EPO and JPO were 37.7 and 31.1 months respectively. (See USPTO (2004) for details, including definition.)

of the R&D process is captured by the parameter β_H, with larger values of β_H reflecting a larger advantage.[10]

We assume that the fact that firm 1 has superior interim R&D knowledge is common knowledge. Without this assumption, PP would not only create a technological spillover, but would also affect firm 2's belief about firm 1's cost; that is, PP would reveal to firm 2 that firm 1's cost is $C(q)$ and not higher. As we shall see below, the investments of firms 1 and 2 in the second phase of the R&D process are strategic substitutes. Hence, firm 1 would wish to ensure that firm 2 is aware of the fact that firm 1 is ahead. To the extent that filing for a patent is the only way to credibly reveal this information, PP would give firm 1 an extra motivation to file for a patent. In this paper, however, we wish to focus on the technological spillover effect and hence we eliminate the effect of PP on firm 2's beliefs by assuming in effect that firm 1 can credibly convey the fact that it has superior R&D knowledge by means other than filing for a patent.[11]

Competition in the product market

At the end of the second phase of the R&D process, the two firms compete in the product market. Instead of assuming a specific type of product market competition, we simply assume that if only one firm succeeds to develop the new technology (this firm can be either firm 1 or 2), then the net present value of its profits is π_{yn} and the net present value of its rival's profits is π_{ny}. If both firms succeed to develop the new technology, then the net present value of their profits is π_{yy}, and if neither firm succeeds, the net present value of their profits is π_{nn}. Throughout, we make the following assumptions:

A1 $\pi_{yn} > \pi_{yy} \geq \pi_{nn} \geq \pi_{ny}$

A2 $\pi_{yn} + \pi_{ny} > 2\pi_{yy}$

[10] The assumption that $\beta_H > \beta_M > \beta_L$ is consistent with Mansfield, Schwartz and Wagner (1981) who estimate that the average ratio between the cost of imitating an existing technology ($\beta_L C(q)$ or $\beta_M C(q)$ in our model) and the cost of innovating it from scratch ($\beta_H C(q)$ in our model) is 0.65.

[11] For papers that study the effect of voluntary disclosure of R&D knowledge on the beliefs of rival firms, see for example Lichtman, Baker and Kraus (2000), Gordon (2004), Jansen (2005), and Gill (2006).

A3 $C'(1) > \pi_{yn} - \pi_{nn}$, and $C''(q) > \pi_{yn} + \pi_{ny} - \pi_{yy} - \pi_{nn}$ for all $q \in [0,1]$

Assumptions A1 and A2 are consistent with a broad class of duopoly models. For example, if the new technology is cost-reducing, then in a Bertrand model with homogeneous products and linear cost functions, $\pi_{yn} > 0 = \pi_{yy} = \pi_{nn} = \pi_{ny}$, while in a Cournot model with homogeneous products, $\pi_{yn} > \pi_{yy} > \pi_{nn} > \pi_{ny}$, and whenever the demand and cost functions are linear, $\pi_{yn} + \pi_{ny} > 2\pi_{yy}$, for a sufficiently large cost reduction.[12] Assumption A3 ensures that the best-response functions of firms 1 and 2 are well behaved.[13]

The solution concept

In Sections 3–5 we solve for the equilibrium in the second phase of the R&D process under the PP and under the CF systems. For each filing system, there are two subgames: a filing subgame if firm 1 applies for a patent at the end of the first phase, and a no-filing subgame if firm 1 does not apply for a patent. We solve for the Nash equilibrium levels of investment in each subgame and then compare the two subgames in order to solve for firm 1's decision on whether or not to file for a patent. In addition, we compare the PP and the CF systems in terms of their effect on the firms' investments in the second phase of the R&D process, and on consumers' surplus and social welfare. Towards the end of the paper in Section 6, we examine the firms' incentives to invest in the first phase of the R&D process.

3 The Pre-Grant Patent Publication (PP) system

When firm 1 files for a patent under the PP system, it can prevent firm 2 from bringing the new technology to the product market (if firm 2 develops it) with probability $\gamma\theta$ which is the

[12] To illustrate, suppose that the inverse demand function is $P = A - x_1 - x_2$, where x_i is the output of firm $i = 1, 2$, and let firm i's marginal cost be 0 if it develops the new technology and $k < A/2$ otherwise. Then, $\pi_{yn} = (A+k)^2/9$, $\pi_{yy} = A^2/9$, $\pi_{nn} = (A-k)^2/9$, and $\pi_{ny} = (A-2k)^2/9$. Hence, Assumption A2 holds provided that $k > 2A/5$.

[13] Note that Assumption A2 and the assumption that $\pi_{yy} \geq \pi_{nn}$ ensure that $\pi_{yn} - \pi_{nn} \geq \pi_{yy} - \pi_{ny}$; hence, $C'(1) > \pi_{yn} - \pi_{nn}$ implies that it is too costly to invest up to the point where developing the new technology becomes a sure thing, regardless of whether the rival firm develops it or not.

probability that a patent is granted and is upheld in court. Hence, $\gamma\theta$ reflects the effective patent protection that firm 1 enjoys. Recalling that the R&D investments of firms 1 and 2 in the second phase of the R&D process, q^1 and q^2, also represent their respective probabilities of success, it follows that the probability that firm 2 will develop the new technology and will be able to bring it to the product market is $q^2(1-\gamma\theta)$. Therefore, when firm 1 files for a patent, the expected payoffs of the two firms are

$$\begin{aligned}\pi^1(q^1,q^2|F) &= q^1\left[q^2\left(1-\gamma\theta\right)\pi_{yy}+\left(1-q^2\left(1-\gamma\theta\right)\right)\pi_{yn}\right] \\ &\quad +(1-q^1)\left[q^2\left(1-\gamma\theta\right)\pi_{ny}+\left(1-q^2\left(1-\gamma\theta\right)\right)\pi_{nn}\right]-C(q^1).\end{aligned} \tag{1}$$

and

$$\begin{aligned}\pi^2(q^1,q^2|F) &= q^1\left[q^2\left(1-\gamma\theta\right)\pi_{yy}+\left(1-q^2\left(1-\gamma\theta\right)\right)\pi_{ny}\right] \\ &\quad +(1-q^1)\left[q^2\left(1-\gamma\theta\right)\pi_{yn}+\left(1-q^2\left(1-\gamma\theta\right)\right)\pi_{nn}\right]-\beta_L C(q^2).\end{aligned} \tag{2}$$

The first line on the right hand side of (1) describes firm 1's payoff when it succeeds to develop the new technology. With probability $q^2(1-\gamma\theta)$, firm 2 also succeeds and can bring the new technology to the product market, so firm 1's payoff is π_{yy}; with probability $1-q^2(1-\gamma\theta)$, firm 2 either fails or else it succeeds but it is prevented from using the new technology in the product market, so firm 1's payoff is π_{yn}. The second line on the right-hand side of (1) describes the corresponding expressions when firm 1 fails to develop the new technology.[14] The interpretation of equation (2) is similar, except that firm 2's cost of R&D is higher than firm 1's cost.

Absent filing, firm 1 cannot prevent firm 2 from using the new technology if firm 2 develops it. Hence, the expected payoffs of the two firms are

$$\pi^1(q^1,q^2|NF)=q^1\left[q^2\pi_{yy}+(1-q^2)\pi_{yn}\right]+(1-q^1)\left[q^2\pi_{ny}+(1-q^2)\pi_{nn}\right]-C(q^1), \tag{3}$$

[14]Note that we assume that firm 1 always sues firm 2 for patent infringement if the latter manages to develop the new commercial technology. Since $\pi_{yn}+\pi_{ny}>2\pi_{nn}$ by Assumptions A1 and A2, suing is obviously optimal when firm 1 also develops the new commercial technology. However, when firm 2 succeeds but firm 1 fails, the two firms can benefit from an ex post licensing agreement, whereby firm 2 pays firm 1 a licening fee in return for firm 1's promise not to sue it for patent infringement. We discuss this possibility in Section 5.4.

and

$$\pi^2(q^1, q^2|NF) = q^1\left[q^2\pi_{yy} + (1-q^2)\pi_{ny}\right] + (1-q^1)\left[q^2\pi_{yn} + (1-q^2)\pi_{nn}\right] - \beta_H C(q^2). \quad (4)$$

These expressions differ from the corresponding expressions in the filling subgame in two ways: first, the probability that firm 2 uses the new technology in the product market is now q^2 instead of $q^2(1-\gamma\theta)$. Second, absent filing, there is no technological spillover so firm 2's cost of investment in the second phase of the R&D process is $\beta_H C(q^2)$ instead of $\beta_L C(q^2)$.

Lemma 1: *(The equilibrium in the PP system.) Assumptions A1-A3 ensure the existence of a unique Nash equilibrium in filing subgame in which* q_F^1, $q_F^2 \in [0,1]$, *and a unique Nash equilibrium in the no-filing subgame in which* q_{NF}^1, $q_{NF}^2 \in [0,1]$. *The equilibrium investment levels are such that* $q_{NF}^2 < q_F^2 < q_F^1 < q_{NF}^1$ *when* $\gamma\theta = 0$ *and* $q_F^2 < q_{NF}^2 < q_{NF}^1 < q_F^1$ *when* $\gamma\theta \geq 1 - \beta_L/\beta_H$.

Figure 2a shows the equilibrium points in the filing subgame, F_0, and the no-filing subgame, NF, when $\gamma\theta = 0$ In that case, firm 1 gets no protection if it files for a patent, so $R^1(q^2|F) = R^1(q^2|NF)$. Since $\beta_H > \beta_L$, the marginal cost of q^2 is higher in the no-filing subgame, so $R^2(q^1|F) > R^2(q^1|NF)$. As $\gamma\theta$ increases, firm 1 gets more patent protection, and as Figure 2b shows, $R^1(q^2|F)$ shifts to the right whereas $R^2(q^1|F)$ shifts down. As a result, the equilibrium point moves southeast from F_0 to F. Figure 2c shows that when $\gamma\theta \geq 1 - \beta_L/\beta_H$, $R^2(q^1|F)$ drops below $R^2(q^1|NF)$, so F is attained southeast of NF. Hence, $q_F^1 > q_{NF}^1$ and $q_F^2 < q_{NF}^2$. In all cases, the assumption that $\beta_H > \beta_L > 1$ ensures that F_0, NF, and F lie below the diagonal, so $q^1 > q^2$. Notice that the best response functions of the two firms are downward sloping - henceq_1 and q_2 are strategic substitutes. This implies in turn that firm 1 has an interest to ensure that firm 2 is aware of the fact that firm 1 has superior interim R&D knowledge even when firm 1 does not file for a patent and does not reveal the contents of it superior knowledge to firm 2.

Now let $\pi_F^1 = \pi^1(q_F^1, q_F^2|F)$ and $\pi_{NF}^1 = \pi^1(q_{NF}^1, q_{NF}^2|NF)$ be the Nash equilibrium payoffs of firm 1 in the filing and in the no-filing subgames, and define π_F^2 and π_{NF}^2 similarly. Then,

Proposition 1: *(firm 1's filing decision under the PP system.) There exists a critical value*

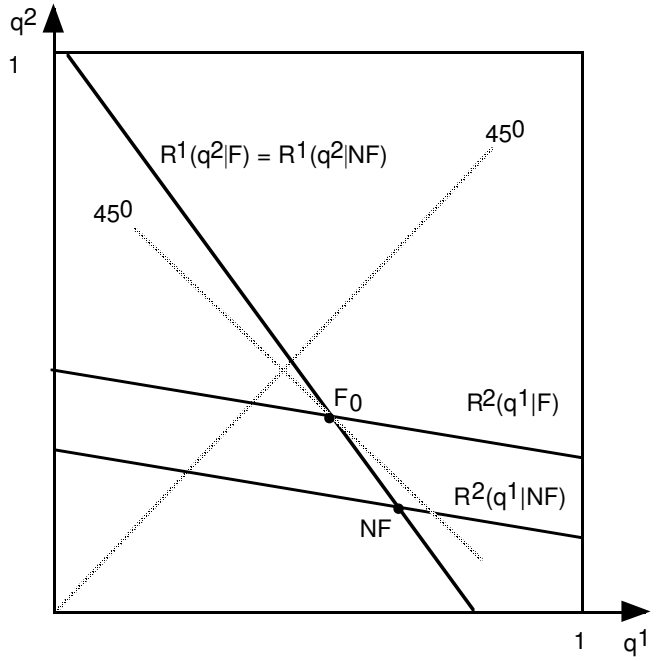


Figure 2a: The best-response functions under the PP system when $\gamma\theta = 0$

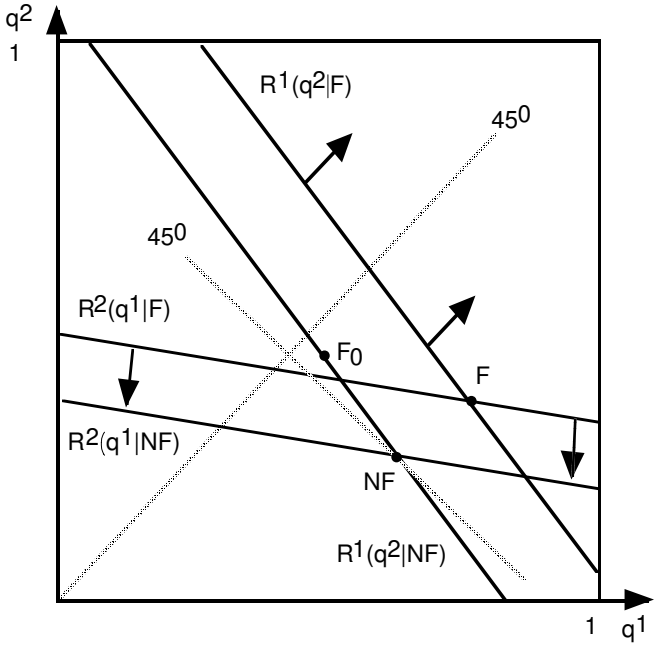


Figure 2b: The best-response functions under the PP system when $0 < \gamma\theta < 1-\beta_H/\beta_L$

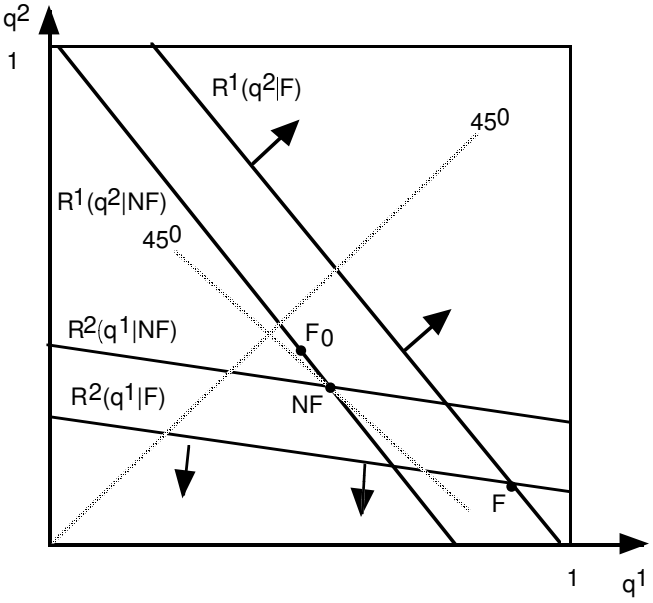


Figure 2c: The best-response functions under the PP system when $\gamma\theta > 1-\beta_H/\beta_L$

of $\gamma\theta$*, denoted* $\widehat{\gamma\theta}$*, where* $\widehat{\gamma\theta} \in (0, 1-\beta_L/\beta_H)$*, such that* $\pi_F^1 \gtreqless \pi_{NF}^1$ *as* $\gamma\theta \gtreqless \widehat{\gamma\theta}$.

Proposition 1 implies that firm 1 files for a patent under the PP system if and only if the effective patent protection, $\gamma\theta$, exceeds a threshold level, $\widehat{\gamma\theta}$. Intuitively, firm 1 does not file for a patent when $\gamma\theta$ is small because then it looses some of its strategic advantage over firm 2, without enjoying much protection against imitation. As $\gamma\theta$ increases, patents receive stronger protection so filing become more attractive to firm 1. When $\gamma\theta > \widehat{\gamma\theta}$, firm 1's benefit from raising its chance to block firm 2 from using the new technology exceeds the corresponding losing some of its strategic advantage and hence it files for a patent.

Proposition 1 also shows that the threshold $\widehat{\gamma\theta}$ is bounded from above by $1-\beta_L/\beta_H$. This implies that we should expect more patent applications when (i) β_L is high (PP creates a relatively small technological spillover so firm 1 does not lose much strategic advantage by filling for a patent), and (ii) β_H is low (firm 1 enjoys only a small advantage at the end of the first phase of the R&D process and hence has little to lose by filing).

4 Confidential Filing

Absent filing, the expected payoffs of the two firms do not depend on the filing system and hence are still given by equations (3) and (4). Consequently, the Nash equilibrium in the no-filing subgame continues to be (q_{NF}^1, q_{NF}^2), as in the PP system. As for the filing subgame, firm 1's expected payoff is also the same across the two filing systems and hence is still given by equation (1).(as before, firm 1 can prevent firm 2 from bringing the new technology to the product market with probability $\gamma\theta$).

Firm 2's expected payoff in the filing subgame is given by

$$\begin{aligned}\overline{\pi}^2(q^1, q^2|F) &= q^1\left[q^2(1-\gamma\theta)\pi_{yy} + (1-q^2(1-\gamma\theta))\pi_{ny}\right] \\ &\quad +(1-q^1)\left[q^2(1-\gamma\theta)\pi_{yn} + (1-q^2(1-\gamma\theta))\pi_{nn}\right] - \beta_\theta C(q^2),\end{aligned} \tag{5}$$

where $\beta_\theta = \theta\beta_M + (1-\theta)\beta_H$. This expression differs from firm 2's corresponding payoff under the PP system (equation (2)) only in the cost of R&D which is now $\beta_\theta C(q^2)$ instead of $\beta_L C(q^2)$. This difference reflects the fact that under the CF system, there is a technological

spillover only if and when a patent is actually granted. This event occurs with probability θ; with probability $1-\theta$, firm 1's patent application is rejected and there is no spillover.

Equation (5) reveals that under the CF system, the likelihood of getting a patent affects the filling subgame not only through the effective patent protection, but also through firm 2's cost of investment in the second phase of the R&D process. Hence, unlike the PP system, now γ and θ have potentially different effects on the equilibrium.

Lemma 2: *(The equilibrium in the CF system.) Assumptions A1-A3 ensure the existence of a unique Nash equilibrium in filing subgame in which* $\overline{q}_F^1, \overline{q}_F^2 \in [0,1]$. *The Nash equilibrium in the no-filing subgame,* (q_{NF}^1, q_{NF}^2), *coincides with that under the PP system. The equilibrium investment levels are such that* $q_{NF}^2 = \overline{q}_F^2 < \overline{q}_F^1 = q_{NF}^1$ *if* $\theta = 0$, $\overline{q}_F^2 < q_{NF}^2 < q_{NF}^1 < \overline{q}_F^1$ *if* $\theta > 0$ *and* $\gamma \geq 1 - \beta_M/\beta_H$, *and either* $q_{NF}^2 < \overline{q}_F^2$, *or* $q_{NF}^1 < \overline{q}_F^1$, *or both, if* $\gamma > 0$ *and* $\gamma < 1 - \beta_M/\beta_H$. *Moreover,* $\overline{q}_F^1 + \overline{q}_F^2 > q_{NF}^1 + q_{NF}^2$ *for all* $\gamma < 1 - \beta_M/\beta_H$.

Lemma 2 is illustrated in Figure 3: the figure shows the best response functions of firms 1 and 2 are downward sloping. Hence, q_1 and q_2 are strategic substitutes as in the PP case. Figure 3a shows that in the extreme case where $\theta = 0$ (no patents are granted), the equilibrium points in the filing subgame, F_0, and in the no-filing subgame, NF, coincide. As θ increases, patents are more likely to be granted, so $\overline{R}^1(q^2|F)$ shifts to the right. Since firm 2 has a lower probability of using the new technology in the product market, the marginal benefit from q^2 falls. Since firm 2 is also more likely to get access to firm 1's knowledge, the marginal cost of q^2 fall as well. Whether $\overline{R}^2(q^1|F)$ shifts up or down, depends on the value of γ. When $\gamma \geq 1 - \beta_L/\beta_H$, patents are likely to be upheld in court, so an increase in θ lowers the marginal benefit from q^2 more than it lowers the marginal cost of q^2. Consequently, as Figure 3b shows, $\overline{R}^2(q^1|F)$ shifts down, so the equilibrium point in the filing subgame, $\overline{F}$, lies southeast of NF. When $\gamma < 1 - \beta_L/\beta_H$, an increase in θ lowers the marginal cost of q^2 by more than it lowers the marginal benefit from q^2, so $\overline{R}^2(q^1|F)$ shifts up. Figure 3c shows that now $\overline{F}$ can lie either northwest, northeast, or southeast of NF, so the comparison between the two subgames is in general ambiguous. Nonetheless, since $\overline{F}$ lies above a 45 degree line passing through NF, the aggregate level of investment is larger in the filing subgame.

Let $\overline{\pi}_F^1 \equiv \pi^1(\overline{q}_F^1, \overline{q}_F^2|F)$ and $\overline{\pi}_F^2 \equiv \pi^2(\overline{q}_F^1, \overline{q}_F^2|F)$ be the equilibrium payoffs of firms 1

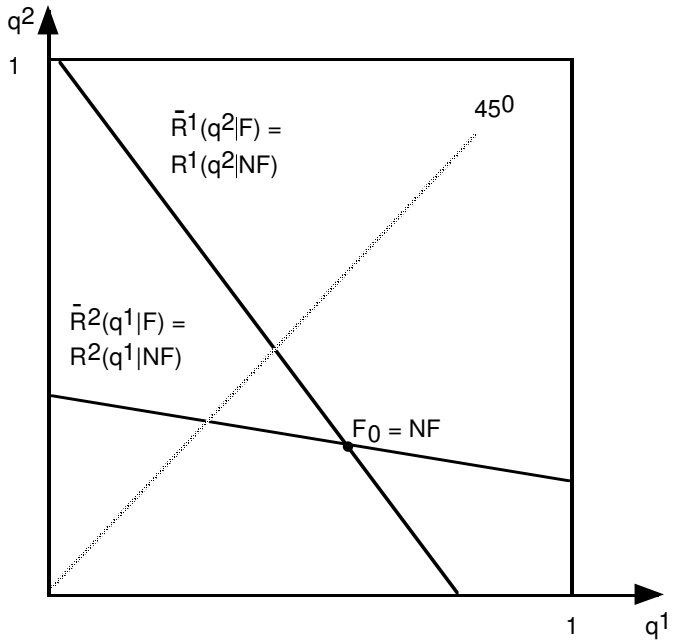


Figure 3a: The best-response functions under the CF sytem when $\theta = 0$

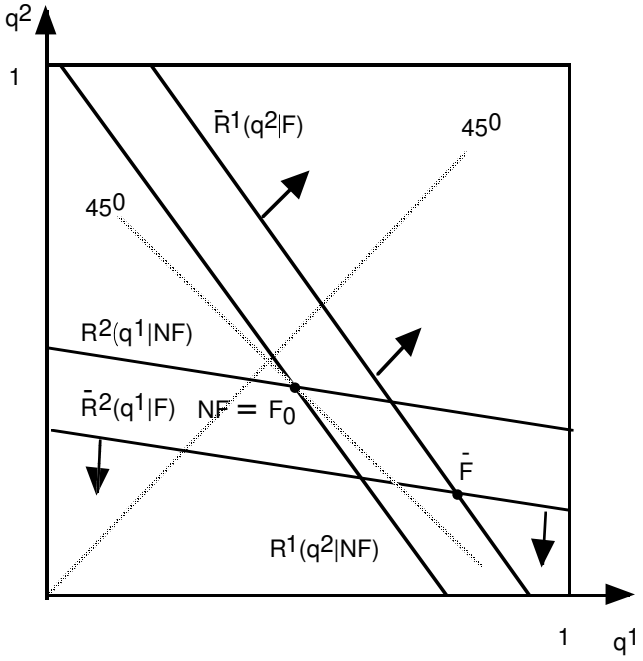


Figure 3b: The best-response functions under the CF system when $\gamma > 1 - \beta_M/\beta_H$.

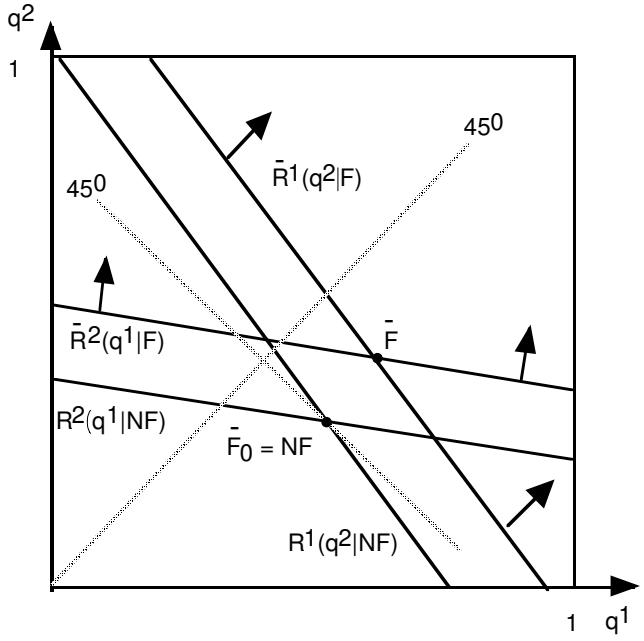


Figure 3c: The best-response functions under the CF system when $\gamma < 1 - \beta_M/\beta_H$.

and 2 in the filing subgame, and recall that the equilibrium payoffs in the no-filing subgame are π^1_{NF} and π^2_{NF}, as in Section 3. Now,

Proposition 2: *(firm 1's filing decision under the CF system.) For each $\theta > 0$, there exists a critical value of γ, denoted $\hat{\gamma}$, where $\hat{\gamma} \in (0, 1 - \beta_L/\beta_H)$, such that $\overline{\pi}^1_F \gtreqless \pi^1_{NF}$ as $\gamma \gtreqless \hat{\gamma}$. Furthermore, $\pi^2_{NF} > \overline{\pi}^2_F$ for all $\gamma > 1 - \beta_M/\beta_H$.*

Proposition 2 implies that given the likelihood of getting a patent, θ, firm 1 files for a patent under the CF system if and only if the likelihood that the patent will be upheld in court exceeds a threshold level, $\hat{\gamma}$. This threshold is bounded from above by $1 - \beta_M/\beta_H$.

5 The implications of PP for R&D, patenting, and welfare

Having examined the two filing systems in isolation, we now compare them in order to determine the impact of PP on firm 1's propensity to file for a patent at the end of the first phase of the R&D process, on the investments of the two firms in the second phase of the R&D process, and on consumer surplus and social welfare.

5.1 The effect of PP on patenting behavior and on the R&D investments

As a preliminary step, we begin by comparing the equilibrium investment levels and expected payoffs under the two filing systems assuming that firm 1 files for a patent (note however that firm 1 need not have the same propensity to file for a patent under the two systems). We do not need to have a similar comparison for the case where firm 1 does not file for a patent since then PP is irrelevant.

Lemma 3: *(Comparing the equilibrium investment levels and expected payoffs in the filing subgame under the two filing systems.) Suppose that firm 1 files for a patent under both systems. Then,*

(i) $\overline{q}_F^2 < q_F^2 < q_F^1 < \overline{q}_F^1$ *and* $q_F^1 + q_F^2 > \overline{q}_F^1 + \overline{q}_F^2$

(ii) $\pi_F^1 < \overline{\pi}_F^1$ *and* $\pi_F^2 > \overline{\pi}_F^2$.

To see the intuition behind Lemma 3 it is useful to look at Figure 4 which illustrates the best response functions of the two firms. The expected marginal cost of firm 2 is higher under the CF system since then there is a technological spillover only if and when firm 1 gets a patent. Consequently, $\overline{R}^2(q^1|F)$ lies below $R^2(q^1|F)$. Since firm 1's best-response function is the same under the two filing systems, the equilibrium point under the PP system, F, is attained northwest of the equilibrium point under the a CF system, $\overline{F}$. Given Assumption A3, $\overline{F}$ lies under a 45 degrees line passing through F, so the aggregate level of investment is larger under the PP system. Part (ii) of Proposition 3 shows that in the filing subgame, PP benefits firm 2 and hurts firm 1.

We are now ready to compare firm 1's propensity to file for a patent under the two systems. To this end, note that the result that $\overline{\pi}_F^1 > \pi_F^1$, together with the fact that by Proposition 1, $\overline{\pi}_F^1 > \pi_{NF}^1$ if $\gamma > \widehat{\gamma\theta}/\theta$ and by Proposition 2, $\overline{\pi}_F^1 > \pi_{NF}^1$ if $\gamma > \hat{\gamma}$, implies the following:

Proposition 3: *(firm 1's filing decision under the PP and CF filing systems.) firm* 1 *does not file for a patent under both filing systems if* $\gamma \leq \hat{\gamma}$*, files for a patent under both systems if* $\gamma > \widehat{\gamma\theta}/\theta$*, and files for a patent only under the CF system if* $\hat{\gamma} < \gamma \leq \widehat{\gamma\theta}/\theta$.

Using Proposition 3, we can now distinguish between three possible cases (see Figure 5): When $\gamma \leq \hat{\gamma}$, patents receive weak protection since they are relatively hard to defend in court. Consequently, firm 1 does not file for a patent under neither filing system so PP is irrelevant. Examples for industries where this might be the case include some mature industries like textile, food processing, and fabricated metal products (Arundel and Kabala 1998, Levin et. al., 1987). When $\gamma > \widehat{\gamma\theta}/\theta$, patents receive relatively strong protection since they are likely to be upheld in court; hence, firm 1 files for a patent under both filing systems. Yet, PP is not irrelevant because it affects the R&D investments of the two firms. Examples for industries where patents are regarded as providing strong protection include pharmaceuticals, organic chemicals, and pesticides (Arundel and Kabala 1998, Levin et. al.,

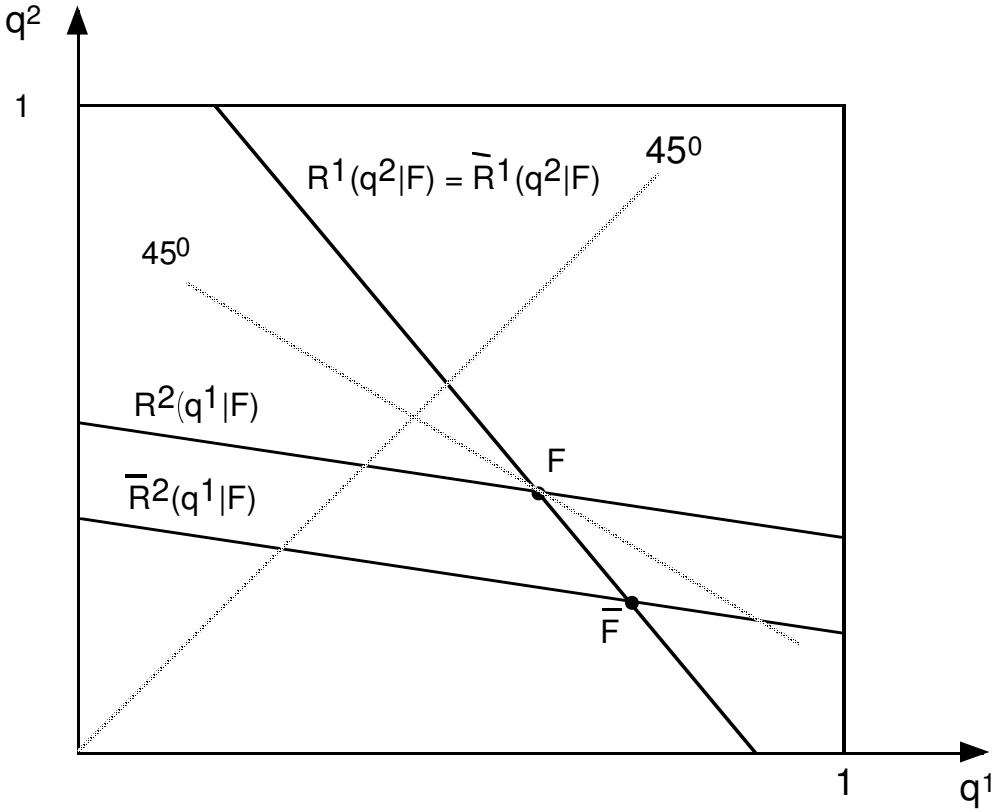


Figure 4: The best-response functions in the filing subgame under the PG-Pub and the CF systems

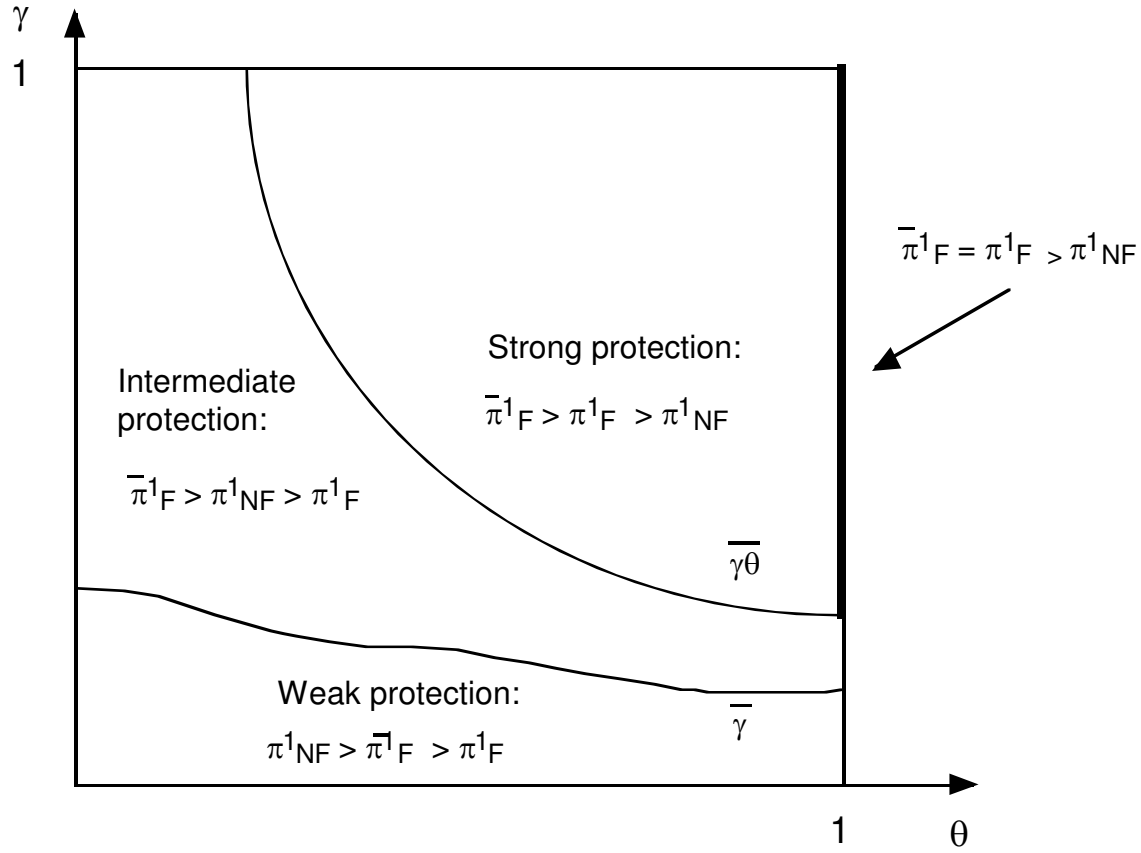


Figure 5: Firm 1's equilibrium profits under the two patent systems. Firm 1 does not file for a patent under both systems when patent protection is weak, files under both systems when patent protection is strong, and files only under the CF system when patent protection is intemediate.

1987, Mansfield, 1986). Finally, when $\hat{\gamma} \leq \gamma \leq \widehat{\gamma\theta}/\theta$, patent protection is intermediate and firm 1 files for a patent only under the CF system. Industries where patents provide an intermediate protection (relative to other forms of protection such as, secrecy, securing a lead time advantage over rivals, learning curve advantages, and investment in sales or service efforts), include chemical products, relatively uncomplicated mechanical equipment, electrical equipment, and Petroleum (Levin et al., 1987, Mansfield, 1986).

The analysis so far reveals that PP has at least three important implications which are corollaries of Propositions 1-3 and Lemmas 2 and 3. First, Proposition 3 implies that there are parameter values for which firm 1 files for a patent under the CF system but not under the PP system. Hence,

Corollary 1: *PP has an adverse effect on the propensity to file for patents.*

Corollary 1 suggests that PP may discourage the dissemination of R&D knowledge, contrary to what many proponents of this system argue.[15] The reason of course is that proponents of PP overlook the fact that PP has an adverse effect on the propensity to file for patents. This adverse effect of PP confirms Gilbert's (1994) intuition that "There is at least a theoretical potential for the publication of applications prior to the patent grants to have adverse incentive effects because of the potential for appropriation of the intellectual property when no patents are ever issued. To avoid appropriation of intellectual property, some investors who otherwise would apply for patents might rely instead on trade secrets protection." However, Proposition 3 qualifies this argument by suggesting that this adverse effect of PP pertains only to industries in which patent protection is intermediate.

[15] For example, in a Congress hearing in February 1997, Rep. Howard Coble (then the chairman of the subcommittee on Courts and Intellectual Property) stated that PP "... will benefit American inventors, innovators, and society at large ... by furthering the constitutional incentive to disseminate information regarding new technologies more rapidly ..." Similarly, Rep. Sue W. Kelly, argued that "It's also an imperative that we have an 18-month publication of patent applications for all inventors ... How can we say that our businesses do not need to know about technology until actually a patent issues? We cannot in good conscious make such judgments because we neither know which technological inventions may be industry-critical, nor from whom or from what source such inventions will arise." Both statements appear in http://commdocs.house.gov/committees/judiciary/hju40523.000/hju40523_0f.htm

Corollary 2: *When patent protection is strong, PP leads to a decrease in* q^1*, and an increase in* q^2 *and in the aggregate level of investment. When patent protection is intermediate, PP leads to a decrease in* q^1*, an increase in* q^2*, and has an ambiguous effect on the aggregate level of investment if* $\gamma > 1 - \beta_M/\beta_H$*. If* $\gamma < 1 - \beta_M/\beta_H$*, PP has an ambiguous effect on* q^1 *and* q^2 *but lowers the aggregate level of investment unambiguously.*

Tepperman (2002) studies the effect of Canada's 1989 Patent Act reform that led to a switch from a confidential filing system with a first-to-invent priority rule to a PP system with a first-to-file priority rule on the behavior of 84 Canadian firms from various industries. He finds that on average, firms have increased their R&D spending following the reform. This finding is consistent with Corollary 2 when patent protection is strong but not when it is intermediate. Tepperman also finds that following the reform, firms have increased their patenting intensity, which is inconsistent with Corollary 1. It should be noted though that Tepperman examines the combined effect of a switch from CF to PP and from first-to-invent to first-to-file, whereas our analysis examines only the effects of a switch from CF to PP. Moreover, the inconsistency may be explained by the fact that firms have stronger incentives to invest in R&D and to patent their inventions under the first-to-file rule than under the first-to-patent rule (Green and Scotchmer, 1990).

Corollary 3: *PP hurts firm* 1 *and benefits firm* 2 *when patent protection is strong and when its is intermediate and* $\gamma > 1 - \beta_L/\beta_H$*.*

The result that PP hurts firm 1 follows by revealed preferences and the fact that firm 1 chooses to file for a patent under the CF system even though it could choose to keep its interim R&D knowledge secret. Putnam (1997) estimates that PP is associated with a \$479 decrease in the mean value of patents. In our model, firm 1's loss is even larger since Putnam's estimate is conditional on a patent being granted, while we examine the impact of PP on the unconditional expected profit of firm 1. The effect of PP on the payoff of firm 2 follows from part (ii) of Lemma 3 when patent protection is strong, and from Proposition 2 when patent protection is intermediate and $\gamma > 1 - \beta_L/\beta_H$.

In the context of our model it is natural to assume that small inventors will mainly play the role of firm 1 while large corporations may play the roles of both firms 1 and 2.

This is because large corporations who are active in product development, are likely to have the capacity and resources needed to absorb the technological spillovers generated by PP, whereas small inventors typically do not have such resources and are mainly busy developing a small number of original inventions. With this interpretation in mind, Corollary 3 suggests that PP is likely to hurt small inventors but may benefit large corporations. This can explain perhaps why the main opposition for adopting a PP system in the U.S. came from small and independent inventors while the main support for PP came from large corporations.

We conclude this section by noting that since firm 1's interim knowledge lowers the cost of R&D from $\beta_H C(q)$ to $C(q)$, it is natural to associate higher values of β_H with higher quality of knowledge. That is, interim knowledge of higher quality lowers the cost of R&D to a greater extent. Given this interpretation, we now ask how PP affects the average quality of firm 1's patent application. Since our model is too general to provide a conclusive answer to this question, we shall make the following assumption:

A4 $C(q) = rq^2/2$, where $r > \pi_{yn} - \pi_{nn}$.

The restriction on r means that choosing $q = 1$ (sure discovery) is too costly and hence never optimal. The restriction on r ensures that Assumption A3 is satisfied.

Proposition 4: *(The effect of PP on the quality of firm 1's patent application.) Given Assumption A4, firm 1 files for a patent under the PP system if and only if $\beta_H \leq \beta_L/(1-\gamma\theta)^2$, whereas under the CF system, it files for a patent if and only if $\beta_H \leq \beta_M/(1-2\gamma+\theta\gamma^2)$. Since $\beta_L/(1-\gamma\theta)^2 < \beta_M/(1-2\gamma+\theta\gamma^2)$, the average quality of 1's patent application is higher under the CF system than under the PP system.*

Roughly speaking, holding β_L and β_M fixed, an increase in β_H raises the cost of patenting since it leads to a larger technological spillover (firm 2's cost of R&D drops from $\beta_H C(q)$ to $\beta_L C(q)$ under the PP system and to $\beta_\theta C(q)$ under the CF system). Therefore, firm 1 files for a patent if and only if β_H is not too large. That is, firm 1 files for a patent only if the quality of its knowledge is not too large. The proposition establishes that the cost of patenting is higher under the PP system, so on average, PP lowers the average quality of firm 1's patent applications relative to the CF system.

5.2 The implications of PP for consumer surplus and social welfare

In this section we study the implications of the technological spillover effect of PP on consumers' surplus and social welfare. Our analysis is done from an ex post point of view since at this point we still have not examined the implications of PP for the incentive of the two firms to accumulate interim R&D knowledge.

Let s_{yy} be the net present value of consumer surplus when both firms develop the new technology, and define s_{yn} and s_{nn} similarly for the cases where only one firm, and when neither firm develop it. The corresponding social welfare is given by the sum of consumer surplus and firms' profits, so $w_{yy} = s_{yy} + 2\pi_{yy}$, $w_{yn} = s_{yn} + \pi_{yn} + \pi_{ny}$, and $w_{nn} = s_{nn} + 2\pi_{nn}$. Since the comparison between consumer surplus and social welfare under the two filing systems is in general very complex, we shall impose Assumption A4. Recalling from Proposition 1 that $\widehat{\gamma\theta}$ is implicitly defined by $\pi_F^1 = \pi_{NF}^1$, and recalling from Proposition 2 that $\hat{\gamma}$ is implicitly defined by $\overline{\pi}_F^1 = \pi_{NF}^1$, it is straightforward to establish that given Assumption A4, $\widehat{\gamma\theta} \equiv 1 - \sqrt{\beta_L/\beta_H}$ and $\hat{\gamma} \equiv 1 - \sqrt{\beta_\theta/\beta_H}/\theta$. Therefore, patent protection is strong if $\gamma > 1 - \sqrt{\beta_\theta/\beta_H}/\theta$, intermediate if $1 - \sqrt{\beta_\theta/\beta_H}/\theta \leq \gamma \leq 1 - \sqrt{\beta_L/\beta_H}/\theta$, and weak if $\gamma < 1 - \sqrt{\beta_\theta/\beta_H}/\theta$. In addition to Assumption A4, we make the following assumptions:

A5 $s_{yy} \geq s_{yn} \geq s_{nn}$, $s_{yy} - s_{yn} \geq s_{yn} - s_{nn}$, and $s_{yn} - s_{nn} > \pi_{nn} - \pi_{ny}$

A6 $w_{yy} \geq w_{yn} \geq w_{nn}$

Assumption A5 implies that the net present value of consumer surplus is increasing with the number of firms that bring the new technology to the product market at an increasing rate. It also implies that if only one firm brings the new technology to the product market, the resulting benefit to consumers outweighs the loss to the firm that does not bring it to the product market. Assumption A6 implies that social welfare is increasing with the number of firms that bring the new technology to the product market. Both assumptions hold in a broad class of oligopoly models; for instance, when the new technology is cost

reducing, Assumptions A5 and A6 hold in the Cournot model with homogeneous products and a linear demand and in the Bertrand model with linear cost functions.

Expected Consumers' surplus

Holding firm 1's interim R&D knowledge constant across the two filing systems, the ex-post expected consumer surplus under both filing systems when firm 1 files for a patent is,

$$\begin{aligned} S(q^1, q^2|F) &= q^1 q^2 \left(1-\gamma\theta\right) s_{yy} + \left(1-q^1\right)\left(1-q^2\left(1-\gamma\theta\right)\right) s_{nn} \\ &\quad + \left[q^1\left(1-q^2\left(1-\gamma\theta\right)\right) + \left(1-q^1\right) q^2\left(1-\gamma\theta\right)\right] s_{yn}. \end{aligned} \tag{6}$$

Likewise, the ex-post expected consumer surplus under both systems absent filing is given by,

$$S(q^1, q^2|NF) = q^1 q^2 s_{yy} + (1-q^1)(1-q^2) s_{nn} + \left[q^1(1-q^2) + (1-q^1)q^2\right] s_{yn}. \tag{7}$$

Let $S_F \equiv S(q_F^1, q_F^2|F)$ be the equilibrium expected value of consumer surplus under the PP system when there is filing, and define $\overline{S}_F \equiv S(\overline{q}_F^1, \overline{q}_F^2|F)$ similarly for the CF system. When firm 1 does not file for a patent, PP plays no role and the equilibrium expected value of consumer surplus under both filing systems is given by $S_{NF} \equiv S(q_{NF}^1, q_{NF}^2|NF)$.

When patent protection is strong, firm 1 files for a patent under both systems. Hence, we need to compare S_F and $\overline{S}_F$. Given Assumption A4, the equilibrium levels of investment under the CF system are

$$\overline{q}_F^1 = \frac{(\pi_{yn} - \pi_{nn})\left(r\beta_\theta + (1-\gamma\theta)^2\Pi\right)}{r^2\beta_\theta - (1-\gamma\theta)^2\Pi^2}, \qquad \overline{q}_F^2 = \frac{(\pi_{yn} - \pi_{nn})(1-\gamma\theta)(r+\Pi)}{r^2\beta_\theta - (1-\gamma\theta)^2\Pi^2}, \tag{8}$$

where $\Pi \equiv \pi_{yy} + \pi_{nn} - \pi_{yn} - \pi_{ny} < 0$ by Assumption A2. Assumptions A1 and A4 ensure that $r > -\Pi$. Together with the assumption that $\beta_H > \beta_L > 1 \geq 1 - \gamma\theta$, this implies in turn that $\overline{q}_F^1$ and $\overline{q}_F^2$ are strictly between 0 and 1. Under the PP system, the investment levels are also given by equation (8), except that now β_L replaces β_θ. Substituting for $\overline{q}_F^1$ and $\overline{q}_F^2$, into (6) yields

$$\begin{aligned} \overline{S}_F &= s_{nn} + \frac{(\pi_{yn} - \pi_{nn})^2\left(1-\gamma\theta\right)^2\left(r+\Pi\right)\left(r\beta_\theta + \left(1-\gamma\theta\right)^2\Pi\right) s}{\left(r^2\beta_\theta - \left(1-\gamma\theta\right)^2\Pi^2\right)^2} \\ &\quad + \frac{(\pi_{yn} - \pi_{nn})\left(r\beta_\theta + \left(1-\gamma\theta\right)^2\left(r+2\Pi\right)\right)\left(s_{yn} - s_{nn}\right)}{r^2\beta_\theta - \left(1-\gamma\theta\right)^2\Pi^2}, \end{aligned} \tag{9}$$

where $s \equiv s_{yy} + s_{nn} - 2s_{yn} > 0$ by Assumption A5. The expression for S_F is identical $\overline{S}_F$, except that β_L replaces β_θ.

In the intermediate protection case, firm 1 files for a patent under the CF system but not under the PP system. Therefore, we need to compare $\overline{S}_F$ and S_{NF}, where $S_{NF} = \overline{S}_F$ when the latter is evaluated at $\theta = 0$ ($\theta = 0$ means that no information is revealed to firm 2, exactly as if firm 1 did not file for a patent).

Proposition 5: *(The effect of PP on consumers.) Suppose that Assumptions A4 and A5 hold and patent protection is intermediate or strong, i.e., $\gamma \geq \hat{\gamma}$ (otherwise PP is irrelevant). Then PP enhances consumer surplus. Moreover, when patent protection is intermediate, the increase in consumer surplus due to PP is larger when γ is larger.*

Intuitively, in the strong protection case, firm 1 files for a patent under both filing systems; but as Lemma 3 shows, firm 1 invests less and firm 2 invests more under the PP system. Given Assumption A4, the latter effect dominates, so the new technology is more likely to reach the product market and this makes consumers better-off. Under intermediate protection, firm 1 files for a patent under the CF system but not under the PP system. To examine how this affects consumers, note that as γ increases, patents are more likely to be upheld in court, so firm 1 is more likely to block firm 2 from bringing the new technology to the product market; hence, consumer surplus under the CF system, $\overline{S}_F$, decreases with γ. On the other hand, under the PP system, firm 1 does not file for a patent so consumer surplus, S_{NF}, is independent of γ. Since $S_{NF} = \overline{S}_F$ when $\gamma = (1 - \sqrt{\beta_\theta/\beta_H})/\theta$, consumers' surplus is higher under a PP system and moreover, the gain of consumers from PP is larger, the larger is γ.

Expected social welfare

Holding the number of inventions fixed across the two filing systems, the expected social welfare when firm 1files for a patent is $W_F = S_F + \pi_F^1 + \overline{\pi}_2^F$ under the PP system, and $\overline{W}_F = \overline{S}_F + \overline{\pi}_F^1 + \overline{\pi}_2^F$ under the CF system. When firm 1does not file for a patent, the ex-post expected social welfare is $W_{NF} = S_{NF} + \pi_{NF}^1 + \pi_{NF}^2$. When patents receive strong protection, firm 1files for a patent under both systems. Hence, the equilibrium ex-post

expected social welfare is $\overline{W}_F$ under the CF system and W_F under the PP system. Given Assumption A4 and using equations (1), (2), (8), and (9),

$$\begin{aligned}\overline{W}_F &= w_{nn} + \frac{(\pi_{yn}-\pi_{nn})^2\left(1-\gamma\theta\right)^2(r+\Pi)\left(r\beta_\theta+\left(1-\gamma\theta\right)^2\Pi\right)s}{\left(r^2\beta_\theta-\left(1-\gamma\theta\right)^2\Pi^2\right)^2} \\ &+\frac{(\pi_{yn}-\pi_{nn})\left(r\beta_\theta+\left(1-\gamma\theta\right)^2(r+2\Pi)\right)(s_{yn}-s_{nn}+\pi_{ny}-\pi_{nn})}{r^2\beta_\theta-\left(1-\gamma\theta\right)^2\Pi^2} \\ &+\frac{(\pi_{yn}-\pi_{nn})^2 r\left(\left(r\beta_\theta+\left(1-\gamma\theta\right)^2\Pi\right)^2+\beta_\theta\left(1-\gamma\theta\right)^2(r+\Pi)^2\right)}{2\left(r^2\beta_\theta-\left(1-\gamma\theta\right)^2\Pi^2\right)^2}\end{aligned} \tag{10}$$

The expression for W_F is identical to $\overline{W}_F$, except that β_L replaces β_θ.

In the intermediate protection case, firm 1files for a patent only under the CF system. Hence, the equilibrium ex-post expected social welfare is $\overline{W}_F$ under the CF system and W_{NF} under the PP system, where W_{NF} is equal to $\overline{W}_F$ when it is evaluated at $\theta = 0$, since under the CF system, the situation when $\theta = 0$ is the same as if firm 1 did not file for a patent.

Using the fact that $\overline{W}_F$ and W_F differ only with respect to θ, and W_F and $\overline{W}_F$ differ only with respect to θ, we prove the following result:

Proposition 6: *(The welfare implications of PP.) Suppose that Assumptions A4–A6 hold and let*

$$\hat{\gamma}(\beta) \equiv \frac{-\Pi\left(Y^2+\sqrt{\beta}Y+\beta-(1-\gamma\theta)^2\right)}{\sqrt{\beta}Y}, \qquad Y \equiv \left(\sqrt{\beta}-(1-\gamma\theta)\right)^{\frac{2}{3}}\left(\sqrt{\beta}+(1-\gamma\theta)\right)^{\frac{1}{3}}.$$

Then,

(i) *a sufficient condition for PP to enhance ex-post expected welfare when patent protection is strong is* $r > \widehat{r}\,(\beta_\theta)$

(ii) *a sufficient condition for PP to enhance (lower) ex-post expected welfare when patent protection is intermediate is* $r > \widehat{r}\,(\beta_\theta)$ *and* $\gamma > \frac{\beta_H-\beta_M}{\beta_H+\beta_\theta}$*; moreover, if* $r > \widehat{r}\,(\beta_\theta)$ *and* $\gamma > \frac{\beta_H-\beta_M}{\beta_H+\beta_\theta}$*, the welfare gain (loss) from to PP is larger (smaller) the larger is* γ*.*

Proposition 6 reveals that when r, which measures the slope of the marginal cost of investment in the second phase of the R&D process is sufficiently large, PP is socially

desirable if patent protection is strong, but depending on the value of γ, it may or may not be socially desirable when patent protection is intermediate. Intuitively, Lemma 3 shows that when patent protection is strong, the gap between q^1 and q^2 is smaller under the PP system. Since the cost functions are convex, this implies that all else equal, the allocation of investments is more efficient under the PP system, and the resulting efficiency gain increases with r. Consequently, when patent protection is strong, PP is surely welfare enhancing when r is sufficiently large. This result is reinforced by the fact that as r increases, the aggregate levels of investment under the two filing systems converge, so the two systems differ mainly with respect to the allocation of investments between the two firms. This argument is driven only by the convexity assumption of the cost function.

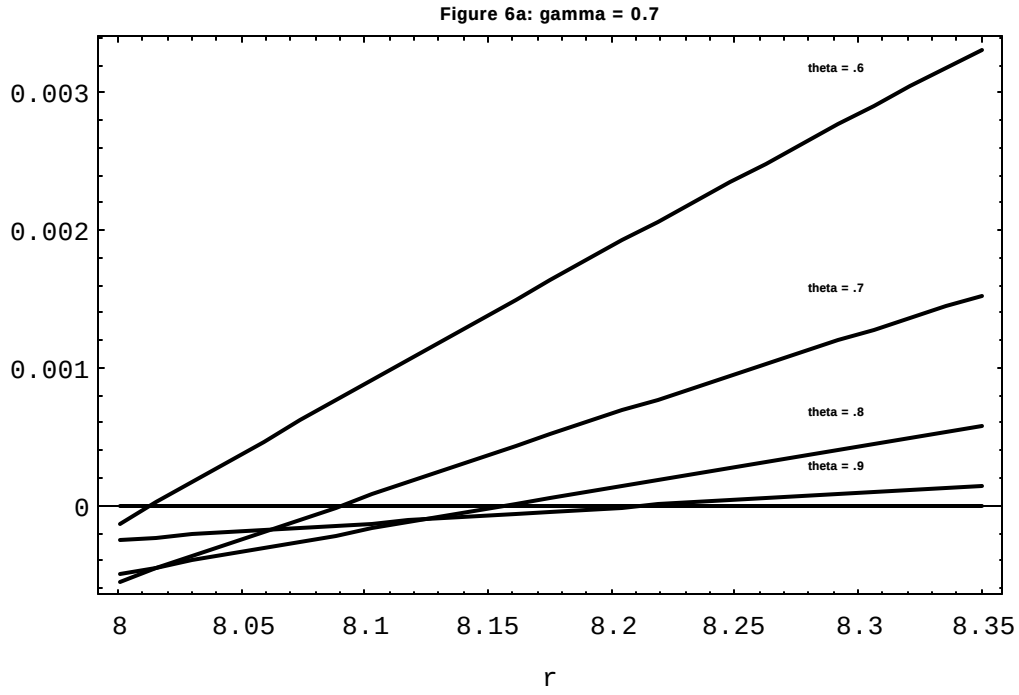
When patent protection is intermediate, things are more complex because the sufficient condition also depends on the likelihood that patents will be upheld in court, γ. The reason that γ matters now is that Lemma 2 shows that when $\gamma > 1 - \beta_M/\beta_H$, the allocation of investments between the two firms is more even under the PP system, whereas when $\gamma < 1 - \beta_M/\beta_H$, the opposite holds. Given the convexity of the cost functions, the allocation of investments is more efficient under the PP system if γ is large and more efficient under the CF system if γ is small.

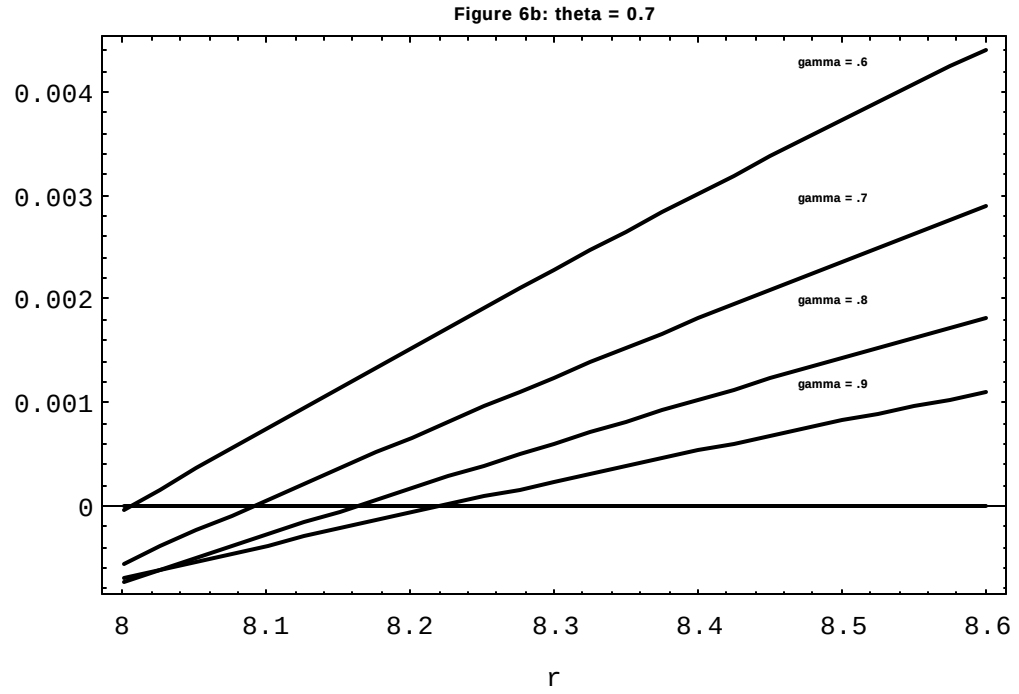
To get a better sense for the welfare implications of PP, we consider the following example.

A Cournot example with a cost-reducing technology

Suppose that the two firms are Cournot competitors and face an inverse demand function $P = 6 - x_1 - x_2$, where x_i is the output of firm i, $i = 1, 2$. In addition, assume that firm i's marginal cost of production is 0 if it develops the new technology and 3 otherwise. Given these assumptions, $\pi_{yn} = 9$, $\pi_{yy} = 4$, $\pi_{nn} = 1$, $\pi_{ny} = 0$, $s_{yy} = 8$, $s_{yn} = 4.5$, and $s_{nn} = 2$; these values are consistent with Assumptions A1, A2, and A5. To ensure that $r > \pi_{yn} - \pi_{nn}$ as Assumption A4 requires, let $r > 8$. The example allows us to derive the precise conditions under which PP enhances or lowers social welfare (Proposition 6 only reports sufficient conditions). In the strong protection case, PP is welfare-enhancing when $W_F - \overline{W}_F > 0$. In Figure 6, we set $\beta_L = \beta_M = 2$ and $\beta_H = 3$ (i.e., $\beta_L/\beta_H = 0.66$, similarly

Figure 6: The change in welfare due to PP in the strong protection case





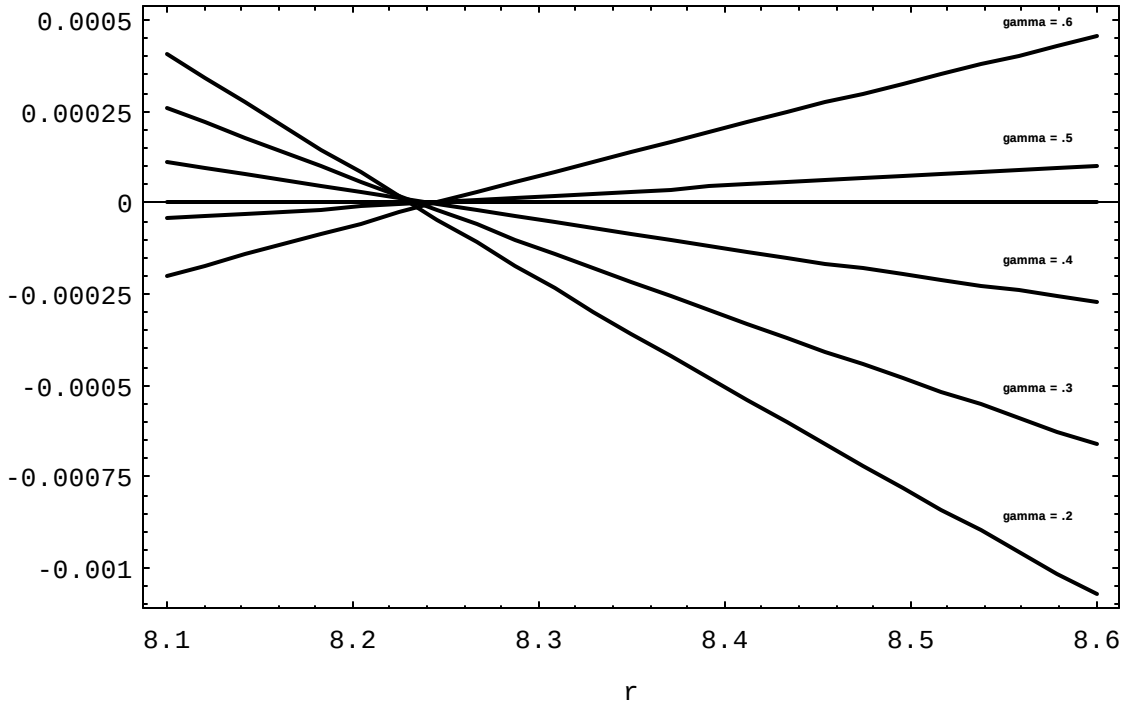
to the ratio of the cost of imitation to the cost of invention obtained by Mansfield, Schwartz, and Wagner (1981)) and present $W_F - \overline{W}_F$ as a function of r for different combinations of γ and θ. The figure shows that PP is welfare-enhancing if and only if r is sufficiently large. Moreover, the figure shows that when PP is socially desirable, it generates a larger welfare gain as θ is smaller (patents are granted with a small probability) and as γ is smaller (patents are unlikely to be upheld in court). To see why, note from equation (8) that the difference between $\overline{q}_F^1 - \overline{q}_F^2$ and $q_F^1 - q_F^2$ widens as γ and θ decrease, so the efficiency gain from PP increases. Thus, PP is more likely to be socially desirable when the marginal cost of developing new products rises sufficiently fast, and the welfare gain (when there is one) is bigger when γ and θ are small.

When the protection of patents is intermediate, PP is welfare-enhancing if $W_{NF} - \overline{W}_F > 0$. In Figure 7, we set $\beta_L = \beta_M = 2$, $\beta_H = 18$, and $\theta = 0.25$ and present $W_{NF} - \overline{W}_F$ as a function of r for five values of γ (we restrict γ to be between 0.118 and 0.667 since protection is intermediate and hence $(1 - \sqrt{\beta_\theta/\beta_H})/\theta \leq \gamma \leq (1 - \sqrt{\beta_L/\beta_H})$). Since $\beta_L/\beta_H = 2/18$, patents create a relatively large technological spillover. When γ is relatively large ($\gamma = 0.5$ and 0.6), PP is welfare enhancing if and only of r is sufficiently large (above 8.241 and 8.245 respectively), whereas when γ is relatively small ($\gamma = 0.2$, 0.3, and 0.4) the opposite is true (r is below 8.231, 8.234, and 8.238, respectively). Figure 7 also shows that when PP is socially desirable, it generates a larger welfare gain when γ is large, i.e., when patents are relatively likely to be upheld in court. As explained above, this is due to the effect of γ on the allocation of investments between the two firms, which in turn affects the efficiency of R&D.

Foreign patent applications and domestic welfare

At least in the U.S., many patent applications are made by foreign inventors whose payoffs should be ignored if we are only interested in domestic welfare. For instance, 45% of all U.S. patent applications in in 2002-2003 were made by non-U.S. residents and 48% of all U.S. patents were issued to non-U.S. residents (USPTO, 2004). To examine how the PP of patent applications filed by foreign inventors affects domestic welfare, suppose that firm 1 is a foreign firm. Then, domestic welfare in the strong protection case is $S_F + \pi_F^2$ under the PP

Figure 7: The change in welfare due to PP in the intermediate protection case (theta = 0.25)



system and $\overline{S}_F + \overline{\pi}_F^2$ under the CF system. Since Proposition 5 and Lemma 3, respectively, imply that $S_F \geq \overline{S}_F$ and $S_F \geq \overline{S}_F$ and $\pi_F^2 \geq \overline{\pi}_F^2$, it is clear that PP enhances domestic welfare. In the intermediate protection case, domestic welfare is still $\overline{S}_F + \overline{\pi}_F^2$ under the CF system, but under the PP system it becomes $S_{NF} + \pi_{NF}^2$. Proposition 5 implies that now, $S_{NF} \geq \overline{S}_F$, while Proposition 2 implies that $\pi_{NF}^2 > \overline{\pi}_F^2$ whenever $\gamma > 1 - \beta_L/\beta_H$. Hence, whenever $\gamma \geq 1 - \beta_L/\beta_H$ so the patent is sufficiently likely to be upheld in court, PP surely enhances domestic welfare. When $\gamma < 1 - \beta_L/\beta_H$, the comparison between π_{NF}^2 and $\overline{\pi}_F^2$ is ambiguous, so we cannot determine the impact on domestic welfare without imposing further structure on the model.

Proposition 7: *(The welfare implications of PP when firm* 1 *is a foreign firm.) If firm* 1 *is a foreign firm then PP always enhances domestic welfare when patent protection is strong. If patent protection is intermediate, a sufficient condition for PP to enhance domestic welfare is that* $\gamma \geq 1 - \beta_L/\beta_H$ *(i.e., the patent is sufficiently likely to be upheld in court).*

Comparing Propositions 6 and 7 reveals that PP is more likely to enhance domestic welfare if firm 1 is a foreign firm. This is because PP always hurts firm 1, so if we ignore firm 1's payoff, we get a more positive picture of the welfare implications of PP. In addition, Proposition 7 shows that in the intermediate protection case, domestic welfare is more likely to increase when patents γ is relatively large. To understand why, note that as γ increases, firm 1 which is now a foreign firm, is more likely to file for a patent and block the domestic firm, firm 2, from using the new technology in the product market. But, in the intermediate protection case, PP induces firm 1 to stop filing for patents, so firm 2 is more likely to use the new technology in the product market if it develops it.

5.3 The timing of PP

In countries that have already adopted the PP system, patent applications are published at 18 months from the filing date (Ragusa 1992). We now examine the impact of the timing of publication on social welfare. To this end, we shall assume that as PP is done earlier, β_L falls (i.e., the cost of imitation under the PP system falls). Then:

Proposition 8: *(The effect of cutting the time between the filing date and the publication date.) Suppose that Assumptions A4–A6 hold. Then, as β_L falls (publication is made earlier), there are fewer patent applications under the PP system, but so long as $r \geq \hat{r}(\beta_L)$, the welfare gain from PP grows when patent applications are made.*

Proposition 8 shows that cutting the time between the filing date and the publication date has mixed welfare effects: on the one hand, it increases the cost of patenting, so less R&D knowledge is disseminated. On the other hand, conditional on patents being filed, the welfare gain from PP increases at least when the cost of R&D is sufficiently convex (note that this is also the condition for PP to be socially desirable). These results are in line with Bloch and Markowitz (1996) who study the effects of delays in the mandatory disclosure of interim R&D knowledge on the incentives to invest in a multi-stage R&D race. They find that shorter disclosure delays weaken the incentives to accumulate interim R&D knowledge, but conditional on an initial discovery being made, shorter disclosure delays enhance welfare by decreasing the expected time of discovering the final commercial product.

5.4 Ex post licensing

Given that $\pi_{yn} + \pi_{ny} > 2\pi_{yy}$ by Assumption A2, it is clear that the two firms will never engage in ex post licensing if firm 1 manages to develop the commercial technology while firm 2 fails. Ex post licensing is efficient however when firm 1 holds a patent on its interim R&D knowledge, but fails to develop the new commercial technology while firm 2 succeeds. This is because the joint payoff of the two firms with ex post licensing is $\pi_{yn}+\pi_{ny}$, while their joint payoff without ex post licensing is either $\pi_{yn} + \pi_{ny}$ if firm 1's patent is not upheld in court and $2\pi_{nn}$ it it is upheld in court, where $\pi_{yn} + \pi_{ny} > 2\pi_{nn}$ by Assumptions A1 and A2. So far we have simply assumed that firm 1 always sues firm 2 for patent infringement and if it wins in court, no firm uses the new technology in the product market. This assumption may be reasonable in cases in which firm 1 has an incentive develop reputation for vigorously protecting its intellectual property in order to deter future infringements on its inventions. In this section we briefly consider the implications of relaxing this assumption.

To this end, suppose that firm 1 holds a patent but fails to develop the new commercial

technology while firm 2 succeeds, and let π_ℓ^1 and π_ℓ^2 denote the payoffs of the two firms if they reach an ex post licensing agreement in this case. To ensure that both firms will accept the agreement, it must be the case that

$$\pi_\ell^1 \geq \gamma\pi_{nn} + (1-\gamma)\pi_{ny}, \qquad \pi_\ell^2 \geq \gamma\pi_{nn} + (1-\gamma)\pi_{yn},$$

where $\gamma\pi_{nn}+(1-\gamma)\pi_{ny}$ and $\gamma\pi_{nn}+(1-\gamma)\pi_{yn}$, respectively, are the expected payoffs of firms 1 and 2 absent an agreement. These payoffs reflect the fact that with probability γ, firm 1 wins in court and both firms earn π_{nn}, while with probability $1-\gamma$, it fails in court and then the payoffs of firms 1 and 2 are π_{ny} and π_{yn}, respectively. Moreover, notice that an ex post licensing agreement generates an expected surplus of $\gamma(\pi_{ny}+\pi_{yn}-2\pi_{nn})$. If firm 1 captures the entire surplus, then its expected payoff becomes $\gamma\pi_{nn}+(1-\gamma)\pi_{ny}+\gamma(\pi_{ny}+\pi_{yn}-2\pi_{nn}) = \pi_{ny}+\gamma(\pi_{yn}-\pi_{nn})$. Likewise, if firm 2 captures the entire surplus, then its expected payoff becomes $\gamma\pi_{nn}+(1-\gamma)\pi_{yn}+\gamma(\pi_{ny}+\pi_{yn}-2\pi_{nn}) = \pi_{yn}-\gamma(\pi_{nn}-\pi_{ny})$. Hence,

$$\pi_\ell^1 \leq \pi_{ny} + \gamma(\pi_{yn}-\pi_{nn}), \qquad \pi_\ell^2 \leq \pi_{yn} - \gamma(\pi_{nn}-\pi_{ny}).$$

Next, notice that ex post licensing (under either the PP or the CF systems) matters only if firm 1 files for a patent, the patent is granted and firm 1 fails to develop the new commercial technology while firm 2 fails. The probability of this event is $\theta(1-q^1)q^2$. Absent ex post licensing, the expected payoffs are $\gamma\pi_{nn}+(1-\gamma)\pi_{ny}$ and $\gamma\pi_{nn}+(1-\gamma)\pi_{yn}$; with ex post licensing, the payoffs are π_ℓ^1 and π_ℓ^2. Hence, ex post licensing increases the expected payoffs of firms 1 and 2 when firm 1 files for a patent by $\theta(1-q^1)q^2\left(\pi_\ell^1-\gamma\pi_{nn}+(1-\gamma)\pi_{ny}\right)$ and $\theta(1-q^1)q^2\left(\pi_\ell^2-\gamma\pi_{nn}+(1-\gamma)\pi_{yn}\right)$, respectively. Since the expected payoffs remain as before when firm 1 does not file for a patent, it is clear that ex post licensing strengthens the incentive of firm 1 to file for a patent. And, given that the extra expected payoff that firm 1 gets from ex post licensing is decreasing with q_1, while the extra expected payoff that firm 2 gets is increasing with q_2, it is clear that under ex post licensing, firm 1 will invest less in R&D while firm 2 will invest more. These changes will be more pronounced the larger θ is since ex post licensing matters only when firm 1 holds a patent.

6 The incentives to accumulate interim R&D knowledge

Thus far we have focused on the implications of PP on the second phase of the R&D process. We now go back to the first phase and ask how PP affects the firms' incentives to accumulate interim R&D knowledge. To this end, let B denote the difference between the expected profits of firm 1 (the leading firm) and firm 2 (the lagging firm). We argue that the filing system that leads to a higher B, provides a stronger incentive to invest in the first phase of the R&D process.[16] As before, we only need to study the strong and the intermediate protection cases since PP is completely irrelevant when patent protection is weak.

In the strong protection case, firm 1 files for a patent under both filing systems, so $B = B_F \equiv \pi_F^1 - \pi_F^2$ under the PP system, and $B = \overline{B}_F \equiv \overline{\pi}_F^1 - \overline{\pi}_F^2$ under the CF system. Since part (ii) of Lemma 3 implies that $\pi_F^1 < \overline{\pi}_F^1$ and $\pi_F^2 > \overline{\pi}_F^2$, it is clear that $B_F < \overline{B}_F$. Hence, PP weakens the incentive to accumulate interim R&D knowledge.

Things are more subtle when protection is intermediate. Now PP induces firm 1 to stop filing for a patent so $B = B_{NF} \equiv \pi_{NF}^1 - \pi_{NF}^2$. Under the CF system firm 1 continues to file for a patent, so as before, $B = \overline{B}_F \equiv \overline{\pi}_F^1 - \overline{\pi}_F^2$. The effect of PP, then, depends on the sign of $B_{NF} - \overline{B}_F$. To examine the sign of this expression, we impose Assumption A4. Then,

$$\overline{B}_F = \frac{(\pi_{yn} - \pi_{nn})(\pi_{yn} + \pi_{nn} - 2\pi_{ny})r\left(\beta_\theta - (1-\gamma\theta)^2\right)}{2\left(r^2\beta_\theta - (1-\gamma\theta)^2\Pi^2\right)}, \tag{11}$$

and B_{NF} is equal to $\overline{B}_F$ when $\theta = 0$.

Proposition 9: *(The effect of PP on the incentives to accumulate interim R&D knowledge.) PP weakens the incentive to accumulate interim R&D knowledge when patent protection is strong, and given Assumption A4, it also weakens the incentive to accumulate R&D knowledge when patent protection is intermediate. Moreover, given Assumption A4, the negative effect of PP on the incentive to accumulate interim R&D knowledge decreases with θ when patent protection is strong but increases with γ when patent protection is intermediate.*

[16] Of course, if the interim knowledge accumulated in the first phase of the R&D process has an independent value of its own, then this value will also affect the incentive to invest in the first phase.

Proposition 9 supports the concern of opponents of PP that PP might discourage investments in R&D. Given the importance of R&D knowledge, this adverse effect of PP should be given a serious consideration. In addition, the proposition shows that as patents become more likely to be upheld in court, this drawback of PP becomes less significant if patent protection is strong, but more significant if patent protection is intermediate. The reason for this difference is that when protection is strong, firm 1 files for a patent under both filing systems. As patents become more likely to be upheld in court, PP is less detrimental to firm 1 and less beneficial to firm 2, so its negative effect on the incentive to invest in the first phase of the R&D process diminishes. When patent protection is intermediate, firm 1 does not file for a patent under the PP system so γ does not affect the incentive to invest. But, since an increase in γ boosts the incentive to invest under the CF system, the detrimental effect of PP on the incentive to invest (i.e., the difference between B_{NF} and $\overline{B}_F$) increases.

7 Conclusion

In this paper we have studied a cumulative innovation model in which one firm (the leading firm) has accumulated interim R&D knowledge and needs to decide whether or not to apply for a patent. The benefit from applying for a patent is that if a patent is granted, the leading firm can sue the lagging firm if the latter manages to develop a new commercial technology on the grounds that this technology infringes on the leading firm's interim R&D knowledge. Applying for a patent is costly however because it allows the lagging firm to get access to the leading firm's superior knowledge and hence diminishes its technological lead. This technological spillover is larger under a PP system because then the lagging firm gets access to the leading firm's interim knowledge through the patent application (even if eventually it is turned down) rather than through the actual patent (if and when it is granted). Our analysis focuses on the implications of this spillover effect of PP.

Our results suggest that PP discourage patent applications in industries in which patent protection is intermediate and may have an adverse effect on the quality of inventions that are patented and on the incentives to invent. At the same time, our results also suggest that, holding the number of inventions fixed, PP may raise the likelihood that new tech-

nologies will reach the product market by either raising the aggregate level of investment in the development of commercial technologies, or by lowering the legal hurdles for introducing such technologies into the market by firms who do not own patents on the underlying basic technologies. This implies that once we fix the number of inventions, PP benefits consumers and may also enhance social welfare. When the inventions are made by foreign firms, the positive effect on domestic welfare is even larger.

Although our model is in many ways quite general (we do not assume a particular type of competition in the product market, we do not need to distinguish between product and process inventions, and we derive many of the results without assuming a particular functional form for the R&D cost functions), it is clear that further analysis is needed before we have a good understanding of the implications of PP. In what follows we discuss few possible extensions. First, we have considered an R&D process with two distinct phases and assumed that the decision to file for a patent (on the interim R&D knowledge) is made at the end of the first phase. In future research it should be interesting to examine a dynamic model of R&D in which the two firms continuously accumulate interim R&D knowledge and can decide not only whether or not to apply for a patent on this knowledge but also at which stage to do that. Filing early is risky because the application is less likely to be accepted. At the same time however, an early application contains less knowledge and hence leads to a smaller technological spillover. Another advantage of applying early is that if a patent is granted, then the firm not only ensures that it can sue rivals if they eventually develop commercial technologies, but also ensures that it will not be sued by rivals. That is, filing early serves not only as an offensive measure but can also play a defensive role.

Second, we have assumed that if the leading firm files for a patent, then it reveals the full extent of its interim R&D knowledge. However, it is possible to extend the analysis by allowing firms to strategically decide how much interim knowledge to include in its patent application. The trade off in this case is that the more knowledge is included in the application, the higher is the probability that a patent will be granted but also the larger is the informational spillover.

Third, our analysis has focused exclusively on the spillover effect of PP; i.e., the fact that PP implies the interim R&D knowledge of the leading firm is revealed to the lagging

firm after 18 months rather than only if and when a patent is issued. As discussed in the Introduction, PP may have an additional effect in the presence of asymmetric information. This asymmetric information could involve the extent of the leading firm's interim R&D knowledge, or the leading firm's beliefs about its chance to eventually develop the new commercial technology, or even the mere fact that the leading firm is also involved in the race to develop the new commercial technology (in case the lagging firm is not even aware of this fact). In all of these cases, if the leading firm files for a patent, then PP allows the lagging firm to get access to the relevant information earlier and for sure. Another possibility that arises under asymmetric information is that firms will be tempted to abuse the PP system and file for a patent in order to fool their rivals into believing that they are ahead in the race even if this is not the case. On the other hand, PP can help to eliminate another form of abuse of the patent system, namely the so-called "submarine" patents, which are patent applications that are intentionally delayed by the applicants until a similar idea is commercialized by someone else (typically a large corporation), at which point the application is completed and entitles the patentholder to collect royalties.[17] PP can eliminate submarine patents by warning rival firms of their existence and hence enabling them to redirect their R&D efforts.

Finally, throughout the paper we have treated the probability that a patent is granted, θ, and the probability that the patent is upheld in court, γ, as exogenous variables. In future research it would be interesting to endogenize these policy variables and ask what are the optimal values θ and γ under the PP system and under the CF system. Moreover, it should be interesting to examine the optimal combination of θ and γ and the delay with which the details of the patent application are revealed to rival firms.

[17] A case in point are the patents that were issued in the 1980's and the 1990's to Jerome Lemelson for bar code-scanning and "machine vision" technologies which he first filed for in 1954 and 1956. According to a story published in the *American Lawyer* in May 1993, Lemelson collected $500 million in royalties from manufacturers who inadvertently infringed on his patents. It should be noted though that there is a disagreement on the significance of submarine patents. For more details, see for instance http://www.ipo.org/submarine.htm.

Appendix

Following is the derivation of the R&D cost functions in the second phase of the R&D process and the proofs of Lemmas 1-3, Propositions 1, 2, 4-6, 8, and 9, and Corollary 2.

Deriving the cost functions of R&D in the second phase of the R&D process: Let c_1 and c_2 be the monetary investments of firms 1 and 2 in the second phase of the R&D process, and let k_1 and k_2 be their respective levels of R&D knowledge. Then the probabilities that firms 1 and 2 will succeed to develop the new technology are given by $q_1 = p(c_1, k_1)$ and $q_2 = p(c_2, k_2)$, where $p(\cdot, \cdot)$ is increasing in both arguments and concave in the first argument. We assume that k_1 is the stock of knowledge that firm 1 has accumulated in the first phase of the R&D process, while $k_2 = \overline{k}_2 + \Delta$ is the sum of the stock of knowledge that firm 2 has accumulated in the first phase, $\overline{k}_2$, and the technological spillover, Δ, where $0 \leq \Delta < k_1 - \overline{k}_2$. The latter is either (i) big and equal to Δ_b if the PP system is in place and firm 1 files for a patent, (ii) small and equal to Δ_s if the CF system is in place and firm 1 is granted a patent, or (iii) is equal to 0 if firm 1 does not apply for a patent or if the CF system is in place and firm 1's patent application is rejected. Now, the cost functions $C(q_1)$ and $\beta_t C(q_2)$, $t = L, M, H$, are implicitly defined by the equations $q_1 = p(C(q_1), k_1)$, $q_2 = p(\beta_L C(q_2), \overline{k}_2 + \Delta_b)$, $q_2 = p(\beta_M C(q_2), \overline{k}_2 + \Delta_s)$, and $q_2 = p(\beta_H C(q_2), \overline{k}_2)$. To illustrate, suppose that $p(c, k) = \sqrt{\frac{2ck}{r}}$ and normalize k_1 to 1. Then, $C(q_1) = \frac{rq_1^2}{2}$ and $C(q_2) = \frac{\beta_t r q_1^2}{2}$, where $\beta_L = 1/\left(\overline{k}_2 + \Delta_b\right)$, $\beta_M = 1/\left(\overline{k}_2 + \Delta_s\right)$, and $\beta_H = 1/\overline{k}_2$. Alternatively, if $p(c, k) = \left(\frac{ck}{ck+r}\right)^2$, then after normalizing k_1 to 1, we obtain, $C(q_1) = \frac{r\sqrt{q_1}}{1-\sqrt{q_1}}$ and $C(q_2) = \beta_t \left(\frac{r\sqrt{q_1}}{1-\sqrt{q_1}}\right)$, where β_t, $t = L, M, H$ is defined as before. ■

Proof of Lemma 1: When firm 1 files for a patent, its best-response function, $R^1(q^2|F)$, is determined implicitly by

$$\frac{\partial \pi^1(q^1, q^2|F)}{\partial q^1} = q^2(1-\gamma\theta)(\pi_{yy} - \pi_{ny}) + \left(1 - q^2(1-\gamma\theta)\right)(\pi_{yn} - \pi_{nn}) - C'(q^1) = 0. \quad (12)$$

Similarly, the best-response function of firm 2, $R^2(q^1|F)$, is determined implicitly by,

$$\frac{\partial \pi^2(q^1, q^2|F)}{\partial q^2} = (1-\gamma\theta)\left[q^1(\pi_{yy} - \pi_{ny}) + (1-q^1)(\pi_{yn} - \pi_{nn})\right] - \beta_L C'(q^2) = 0. \quad (13)$$

Assumptions A1 and A3 ensure that $R^1(q^2|F)$ and $R^2(q^1|F)$ are well-defined, single-valued, and downward sloping in the (q^1, q^2) space. Hence, q^1 and q^2 are strategic substitutes. A Nash equilibrium in the filing subgame, (q_F^1, q_F^2), is determined by the intersection of $R^1(q^2|F)$ and $R^2(q^1|F)$. We now prove that Assumptions A1–A3 ensure that $R^1(q^2|F)$ and $R^2(q^1|F)$ intersect only once in the unit square.

To this end, let rewrite (12) and (13) as follows:

$$q^2 = H_1(q^1) = \frac{(\pi_{yn} - \pi_{nn}) - C'(q^1)}{-(1-\gamma\theta)\Pi},$$

and

$$q^1 = H_2(q^2) = \frac{(1-\gamma\theta)(\pi_{yn} - \pi_{nn}) - \beta_L C'(q^2)}{-(1-\gamma\theta)\Pi},$$

where $\Pi = \pi_{yy} + \pi_{nn} - \pi_{yn} - \pi_{ny} \leq 2\pi_{yy} - \pi_{yn} - \pi_{ny} < 0$ (the first inequality follows because $\pi_{yy} > \pi_{nn}$ by Assumption A1 and the second equality follows from Assumption A2). $H_1(q^2)$ and $H_2(q^1)$ intersect in the (q^1, q^2) space in the unit square (recall that q^1 and q^2 are probabilities and hence must be between 0 and 1) provided that (i) $H_1(0) > 1$, (ii) $H_1(1) < 0$, (iii) $H_2(1) < 1$, (iv) $H_2(0) > 1$. Condition (ii) is satisfied if $C'(1) > \pi_{yn} - \pi_{nn}$, which is ensured by Assumption A3. Condition (iii) is satisfied if $C'(1) > (1-\gamma\theta)(\pi_{yn} - \pi_{nn})/\beta_L$; since $\beta_L > 1 > 1 - \gamma\theta$, this inequality is implied by Assumption A3. Since $\Pi < 0$ and recalling from Assumption A3 that $C'(0) = 0$, condition (i) and (iv) are both satisfied if $\pi_{yn} - \pi_{nn} > -(1-\gamma\theta)\Pi$. It is now easy to verify that the last inequality holds since $\pi_{yy} > \pi_{ny}$.

To prove uniqueness, note that the slopes of $R^1(q^2|F)$ and $R^2(q^1|F)$ are given by $C''(q^1)/\left((1-\gamma\theta)\Pi\right)$ and $\left((1-\gamma\theta)\Pi\right)/\beta_L C''(q^2)$, respectively. Given Assumption A3, $\frac{C''(q^1)}{(1-\gamma\theta)\Pi} < -1 < \frac{(1-\gamma\theta)\Pi}{\beta_L C''(q^2)}$, which in turn implies that $R^1(q^2|F)$ and $R^2(q^1|F)$ intersect only once.

When firm 1 does not file for a patent, the two best-response function, $R^1\left(q^2|NF\right)$ and $R^2(q^1|NF)$ respectively, are implicitly defined by:

$$\frac{\partial \pi^1(q^1, q^2|NF)}{\partial q^1} = q^2(\pi_{yy} - \pi_{ny}) + (1-q^2)(\pi_{yn} - \pi_{nn}) - C'(q^1) = 0, \tag{14}$$

and

$$\frac{\partial \pi^2(q^1, q^2|NF)}{\partial q^2} = q^1(\pi_{yy} - \pi_{ny}) + (1-q^1)(\pi_{yn} - \pi_{nn}) - \beta_H C'(q^2) = 0. \tag{15}$$

Assumptions A1 and A3 ensure that $R^1(q^2|NF)$ and $R^2(q^1|NF)$ are well-defined, single-valued, and downward sloping. A Nash equilibrium in the no-filing subgame, (q^1_{NF}, q^2_{NF}), is defined by the intersection of $R^1(q^2|NF)$ and $R^2(q^1|NF)$. The proof that Assumptions A1–A3 ensure that $R^1(q^2|NF)$ and $R^2(q^1|NF)$ intersect only once in the unit square is similar to the corresponding proof in the filing subgame and is therefore omitted.

Next, we turn to the equilibrium levels of investment. Since γ and θ do not appear in (14) and (15), q^1_{NF} and q^2_{NF} are independent of γ and θ. On the other hand, Assumptions A1 and A2 ensure that $\pi_{yy}+\pi_{nn}-\pi_{yn}-\pi_{ny} < 2\pi_{yy}-\pi_{yn}-\pi_{ny} < 0$, so (12) and (13) imply that $\partial R^1(q^2|F)/\partial(\gamma\theta) > 0$ and $\partial R^2(q^1|F)/\partial(\gamma\theta) < 0$. Since q^1 and q^2 are strategic substitutes, it follows that q^1_F increases and q^2_F decreases with $\gamma\theta$.

Now suppose that $\gamma\theta = 0$. Then, by (12) and (14), $R^1(q^2|F) = R^1(q^2|NF)$. Since $\beta_L < \beta_H$, equations (13) and (15) imply that $R^2(q^1|F) > R^2(q^1|NF)$ for all q^1 and since q^1 and q^2 are strategic substitutes, it follows that $q^1_F < q^1_{NF}$ and $q^2_F > q^2_{NF}$. To prove that $q^2_F < q^1_F$, note that if $\theta\gamma = 0$ and $\beta_L = 1$, equations (12) and (13) are symmetric, and hence $q^2_F = q^1_F$. As β_L increases from 1, $R^2(q^1|F)$ shifts down and since the best-response functions are downward sloping, it must be that $q^2_F < q^1_F$. The proof that $q^2_{NF} < q^1_{NF}$ is similar to the proof that $q^2_F < q^1_F$.

Finally, suppose that $\gamma\theta \geq 1 - \beta_L/\beta_H$, and rewrite (13) as follows:

$$\frac{\partial \pi^2(q^1, q^2|F)}{\partial q^2} = q^1(\pi_{yy} - \pi_{ny}) + (1 - q^1)(\pi_{yn} - \pi_{nn}) - \frac{\beta_L C'(q^1)}{1 - \gamma\theta} = 0. \tag{16}$$

Since $\gamma\theta \geq 1 - \beta_L/\beta_H$, the third term here exceeds the third term in (15), so $R^2(q^1|F) \leq R^2(q^1|NF)$. Together with the fact that by (12) and (14), $R^1(q^2|F) > R^1(q^2|NF)$ for all $\gamma\theta > 0$, it follows that $q^1_F > q^1_{NF}$ and $q^2_F < q^2_{NF}$. ■

Proof of Proposition 1: By equations (3) and (4), π^1_{NF} and π^2_{NF} are independent of γ and θ. Using the envelope theorem, equation (1) implies that Assumption A1 ensures that the expression inside the square brackets and $\partial\pi^1_F/\partial q^2$ are negative. Since $\partial q^2_F/\partial(\gamma\theta) < 0$ by Lemma **??**, it follows that $\partial\pi^1_F/\partial(\theta\gamma) > 0$. The proof that $\partial\pi^2_F/\partial(\gamma\theta) < 0$ is analogous.

To prove the existence of $\widehat{\gamma\theta} \in (0, 1 - \beta_L/\beta_H)$, such that $\pi^1_F \gtreqless \pi^1_{NF}$ as $\gamma\theta \gtreqless \widehat{\gamma\theta}$, note that $\hat{\gamma\theta}$ is defined implicitly $\pi^1_F = \pi^1_{NF}$. Since π^1_F increases with $\gamma\theta$, whereas π^1_{NF} is independent of $\gamma\theta$, it is sufficient to show that $\pi^1_F < \pi^1_{NF}$ if $\gamma\theta = 0$ and conversely if

$\gamma\theta = 1 - \beta_L/\beta_H$. If $\gamma\theta = 0$, equations (1) and (3) imply that $\pi^1(q^1, q^2|F) = \pi^1(q^1, q^2|NF)$. Consequently,

$$\pi^1(q_F^1, q_{NF}^2|F) = \pi^1(q_F^1, q_{NF}^2|NF) \leq \pi_{NF}^1,$$

where the strict inequality follows where the strict inequality follows because $\partial\pi^1(q^1, q^2|F)/\partial q^2 < 0$ and because by Lemma **??**, $q_F^2 > q_{NF}^2$ when $\gamma\theta = 0$, and the weak inequality is implied by revealed preferences (i.e., the definition of q_{NF}^1). Next suppose that $\gamma\theta = 1 - \beta_L/\beta_H$. Then Lemma **??** indicates that $q_F^2 < q_{NF}^2$. Using equations (1) and (3) and Assumption A1, it is easy to show that $\pi^1(q^1, q^2|F) > \pi^1(q^1, q^2|NF)$ for all $q^2 > 0$ and all $\gamma, \theta > 0$, so

$$\pi_F^1 \geq \pi^1(q_{NF}^1, q_F^2|F) > \pi^1(q_{NF}^1, q_F^2|NF) = \pi_{NF}^1,$$

where the left inequality is implied by revealed preferences and the right inequality follows because $\partial\pi^1(q^1, q^2|F)/\partial q < 0$ and $q_F^2 < q_{NF}^2$. ■

Proof of Lemma 2: The expected payoff functions in the no-filing subgame do not depend on the filing system. Hence the Nash equilibrium in the no-filing is once again (q_{NF}^1, q_{NF}^2). Moreover, since firm 1's expected payoff does not depend on the filing system, its best-response function in the filing subgame, $R^1(q^2|F)$, continues to be defined implicitly by equation 12. The best-response function of firm 2, $\overline{R}^2(q^1|F)$, is now defined implicitly by,

$$\frac{\partial\overline{\pi}^2(q^1, q^2|F)}{\partial q^2} = (1 - \gamma\theta)\left[q^1(\pi_{yy} - \pi_{ny}) + (1 - q^1)(\pi_{yn} - \pi_{nn})\right] - \beta_\theta C'(q^2) = 0, \qquad (17)$$

where $\beta_\theta \equiv \theta\beta_M + (1 - \theta)\beta_H$. Assumptions A1 and A3 ensure that $\overline{R}^2(q^1|F)$ is well-defined, downward sloping in the (q^1, q^2) space. A Nash equilibrium in the filing subgame, $(\overline{q}_F^1, \overline{q}_F^2)$, by the intersection of $R^1(q^2|F)$ and $\overline{R}^2(q^1|F)$. The proof that Assumptions A1–A3 ensure and $\overline{R}^2(q^1|F)$ intersect only once in the unit square is similar to that in Lemma 1 and is therefore omitted.

Next, we turn to the properties of the equilibrium investment levels. First, (12) and (17) reveal that $\partial\pi^1(q^2|F)/\partial\gamma > 0$ and $\partial\pi^2(q^1|F)/\partial\gamma < 0$. Since q^1 and q^2 are strategic substitutes and steeper than $\overline{R}^2(q^1|F)$, it follows that $\overline{q}_F^1$ increases and $\overline{q}_F^2$ decreases with γ. Second, from (12) it is clear that $\partial R^1(q^2|F)/\partial\theta > 0$. Using (17), we get:

$$sign\left[\frac{\partial\overline{R}^2(q^1|F)}{\partial\theta}\right] = sign\left[\gamma\left[q_F^1(\pi_{yy} - \pi_{ny}) + (1 - q_F^1)(\pi_{yn} - \pi_{nn})\right] - (\beta_M - \beta_H)C'(\overline{q}_F^2)\right].$$

Substitution for $C'(\overline{q}_F^2)$ from equation (17) and rearranging terms,

$$sign\left[\frac{\partial \overline{R}^2(q^1|F)}{\partial \theta}\right] = sign\left[\frac{\beta_H}{\beta_\theta}\left[q_F^1(\pi_{yy}-\pi_{ny})+(1-q_F^1)(\pi_{yn}-\pi_{nn})\right]\left[\left(1-\frac{\beta_M}{\beta_H}\right)-\gamma\right]\right].$$

Since the expression outside the square brackets is positive, it follows that $\partial \overline{R}^2(q^1|F)/\partial\theta \gtreqless 0$ as $\gamma \lesseqgtr 1-\beta_M/\beta_H$. Thus, when $\gamma > 1-\beta_M/\beta_H$, $\partial \overline{R}^2(q^1|F)/\partial\theta < 0$. Together with the fact that $\partial \overline{R}^1(q^2|F)/\partial\theta > 0$ and the fact that q^1 and q^2 are strategic substitutes and $R^1(q^2|F)$ is steeper than $\overline{R}^2(q^1|F)$, this implies that $\overline{q}_F^1$ increases and $\overline{q}_F^2$ decreases. When $\gamma < 1-\beta_M/\beta_H$, then $\partial R^2(q^1|F)/\partial\theta > 0$. Since $\partial \overline{R}^1(q^2|F)/\partial\theta > 0$ as well, it follows that either $\overline{q}_F^1$ increases, or $\overline{q}_F^2$ increases, or both.

When $\theta = 0$, (12) coincides with (14) and (17) coincides with (15), so $R^1(q^2|F) = R^1(q^2|NF)$ and $\overline{R}^2(q^1|F) = \overline{R}^2(q^1|NF)$. The proof that $\overline{q}_F^1 > \overline{q}_F^2$ when $\theta = 0$ and the proof for the case where $\theta > 0$ are similar to the corresponding proofs in Lemma 1.

Finally, suppose that $\gamma = 1-\beta_M/\beta_H$. Then, $\overline{R}^2(q^1|F) = R^2(q^1|NF)$, so $(\overline{q}_F^1, \overline{q}_F^2)$ and (q_{NF}^1, q_{NF}^2) lie on the same curve in the (q^1, q^2) space, with $(\overline{q}_F^1, \overline{q}_F^2)$ being southeast of (q_{NF}^1, q_{NF}^2). Using (17), the slope of this curve is $\partial \overline{R}^2(q^1|F)/\partial q^1 = -(1-\gamma\theta)\Pi/\beta_\theta C''(q_F^2)$. Given Assumption A3, $C''(q) > -\Pi$ for all $q \in [0,1]$, so $\partial \overline{R}^2(q^1|F)/\partial q^1 > -1$, implying that $(\overline{q}_F^1, \overline{q}_F^2)$ lies above a 45 degrees line passing through (q_{NF}^1, q_{NF}^2). Consequently, $\overline{q}_F^1 + \overline{q}_F^2 > q_{NF}^1 + q_{NF}^2$. When $\gamma < 1-\beta_M/\beta_H$, $\overline{R}^2(q^1|F)$ shifts up thereby reinforcing the result. ■

Proof of Proposition 2: The proof that $\hat{\gamma}$ exists and decreases with β_L and increases with β_H is similar to the proof of Proposition 1 and is therefore omitted. To compare the π_F^2 and π_{NF}^2, suppose that $\gamma > 1-\beta_M/\beta_H$. Using equation (4) and recalling that $\overline{\pi}^2(q^1, q^2|F)$ is given by (2) with β_θ instead of β_L, we get,

$$\pi^2(\overline{q}_F^1, \overline{q}_F^2|NF) - \pi_F^2 = \theta\gamma\overline{q}_F^2\left[\overline{q}_F^1(\pi_{yy}-\pi_{yn})-(1-\overline{q}_F^1)(\pi_{yn}-\pi_{nn})\right] - \theta(\beta_H-\beta_M)C(\overline{q}_F^2).$$

Substituting for the square bracketed term from equation (17) and recalling that $C(q)$ is strictly convex,

$$\begin{aligned}\pi^2(\overline{q}_F^1, \overline{q}_F^2|NF) - \pi_F^2 &= \theta\left[\gamma\beta_\theta\overline{q}_F^2 C'(\overline{q}_F^2) - \theta(\beta_H-\beta_M)C(\overline{q}_F^2)\right] \\ &> \frac{\theta\beta_H C(\overline{q}_F^2)}{1-\gamma\theta}\left[\gamma-\left(1-\frac{\beta_M}{\beta_H}\right)\right] > 0.\end{aligned}$$

Using this inequality,

$$\pi^2_{NF} \geq \pi^2(q^1_{NF}, \overline{q}^2_F|NF) > \pi^2(\overline{q}^1_F, \overline{q}^2_F|NF) > \overline{\pi}^2_F,$$

where the first (weak) inequality follows by revealed preferences, and the second (strict) inequality follows because $\partial\pi^2(q^1, a^2|NF)/\partial q^1 < 0$ and $\overline{q}^1_F > q^1_{NF}$ for all $\gamma > 1 - \beta_M/\beta_H$. ■

Proof of Lemma 3: (i) Equations (13) and (17) and the assumption that $\beta_0 > \beta_L$, imply that $\overline{R}^2(q^1|F) < R^2(q^1|F)$. Since firm 1's best-response function is the same under the PP and CF systems and q^1 and q^2 are strategic substitutes, it follows that $q^1_F < \overline{q}^1_F$ and $q^2_F > \overline{q}^2_F$. To prove that $q^2_F < q^1_F$, note that if $\gamma\theta = 0$ and $\beta_L = 1$, equations (12) and (13) are symmetric and hence $q^2_F = q^1_F$. As $\gamma\theta$ increases from 0 and β_L increases from 1, $\overline{R}^2(q^1|F)$ shifts down while $R^1(q^2|F)$ shifts to the right; since the two best-response functions are downward sloping, it follows that $q^2_F < q^1_F$. To examine the aggregate level of investment, note that since firm 1's best-response function in the filing subgame is the same under both filing systems, $(\overline{q}^1_F, \overline{q}^2_F)$ and (q^1_F, q^2_F) lie on the same curve in the (q^1, q^2) space, with $(\overline{q}^1_F, \overline{q}^2_F)$ being southeast of (q^1_F, q^2_F). Using equation (3), the slope of this curve is $\partial R^1(q^2|F)/\partial q^2 = (1-\gamma\theta)\Pi/C''(q^1_F)$. Given Assumption A3, $C''(q) > -\Pi$ for all $q \in [0,1]$, so $\partial R^1(q^2|F)/\partial q^2 > -1$, implying that $(\overline{q}^1_F, \overline{q}^2_F)$ lies below a 45 degrees line passing through (q^1_F, q^2_F). Consequently, $\overline{q}^1_F + \overline{q}^2_F \leq q^1_F + q^2_F$.

(ii) First, note that

$$\pi^1_F < \pi^1(q^1_F, \overline{q}^2_F|F) \leq \overline{\pi}^1_F,$$

where the left inequality follows since $\partial\pi^1(q^1, q^2|F)/\partial q^2 < 0$ and since $q^2_F > \overline{q}^2_F$, and the right inequality follows by revealed preferences. Second, using equation (4) and the fact that $\overline{\pi}_2(q^1, q^2|F)$ is given by (2) with β_θ instead of β_L, it follows that $\pi^2(q^1, q^2|F) > \overline{\pi}^2(q^1, q^2|F)$. Hence,

$$\pi^2_F \geq \pi^1_F > \pi^2(q^1_F, \overline{q}^2_F|F) > \pi^2(\overline{q}^1_F, \overline{q}^2_F|F) \geq \overline{\pi}^2_F,$$

where the left inequality follows from revealed preferences and the middle inequality follows since $\partial\overline{\pi}^2(q^1, q^2|F)/\partial q^1 < 0$ and $q^1_F < \overline{q}^1_F$. ■

Proof of Corollary 2: Proposition 3 implies that when patent protection is strong, the equilibrium investment levels are q_F^1 and q_F^2 under the PP system and $\overline{q}_F^1$ and $\overline{q}_F^2$ under the CF system. The effect of PP on the investment levels in this case follows immediately from part (i) of Lemma 3. When patent protection is intermediate, Proposition 3 implies that the equilibrium investment levels are q_{NF}^1 and q_{NF}^2 under the PP system and $\overline{q}_F^1$ and $\overline{q}_F^2$ under the CF system. The effect of PP on the investment levels in this case follows immediately from part (ii) of Lemma 2. ■

Proof of Proposition 4: Given Assumption A4, firm 1's expected payoff if it files for a patent under the PP system is

$$\pi_F^1 = \pi_{nn} + \frac{(\pi_{yn} - \pi_{nn})^2 r \left(r\beta_L + (1-\gamma\theta)^2\Pi\right)^2}{2\left(r^2\beta_L - (1-\gamma\theta)^2\Pi^2\right)^2} + \frac{(\pi_{yn} - \pi_{nn})(\pi_{nn} - \pi_{ny})(r+\Pi)(1-\gamma\theta)^2}{r^2\beta_L - (1-\gamma\theta)^2\Pi^2}.$$

If firm 1 does not file for a patent, its expected payoff, π_{NF}^1, is given by a similar expression with β_H replacing β_L and $\theta = 0$. Clearly, π_F^1 is independent of β_H while a straightforward (though tedious) differentiation reveals that given Assumption A2 and the assumptions that $r > \pi_{yn} - \pi_{nn}$ and $\beta_L > 1 \geq 1 - \gamma\theta$, π_{NF}^1 is increasing with β_H. Now, setting $\pi_F^1 = \pi_{NF}^1$ and solving for β_H, the largest β_H for which firm 1 still files for a patent under the PP system is $\beta_L/(1-\gamma\theta)^2$.

Under the CF system, the expected payoff of firm 1 if it files for a patent, $\overline{\pi}_F^1$ is similar to π_F^1, except that $\beta_\theta = \theta\beta_M + (1-\theta)\beta_H$ replaces β_L. Now things are more complex since both $\overline{\pi}_F^1$ and π_{NF}^1 depend on β_H. Setting $\overline{\pi}_F^1 = \pi_{NF}^1$ and solving for β_H yields three solutions, but two of them are less than β_M and are therefore irrelevant (by assumption, $\beta_H > \beta_M$. The third solution is equal to $\beta_M/(1 - 2\gamma + \theta\gamma^2)$. Since the derivative of $\pi_F^1 - \pi_{NF}^1$ is decreasing at $\beta_H = \beta_M/(1 - 2\gamma + \theta\gamma^2)$ it follows that firm 1 files for a patent if and only if $\beta_H < \beta_M/(1 - 2\gamma + \theta\gamma^2)$. ■

Proof of Proposition 5: In the strong protection case, we need to compare $\overline{S}_F$ (consumers' surplus under the CF system) and S_F (consumers' surplus under the PP system). Now,

$$\begin{aligned} S_F - \overline{S}_F \;=\; & \frac{(\pi_{yn} - \pi_{nn})^2 r (1-\gamma\theta)^2 (r+\Pi)^2 (\beta_\theta - \beta_L)(\beta_\theta - \beta_L)(s_{yn} - s_{nn})}{\left(r\beta_\theta + (1-\gamma\theta)^2\Pi^2\right)\left(r^2\beta_L - (1-\gamma\theta)^2\Pi^2\right)} \\ & + (\pi_{yn} - \pi_{nn})^2 (r+\Pi)(1-\gamma\theta)\left[\frac{r\beta_L - (1-\gamma\theta)^2\Pi}{\left(r^2\beta_L - (1-\gamma\theta)^2\Pi^2\right)^2} - \frac{r\beta_\theta - (1-\gamma\theta)^2\Pi}{\left(r^2\beta_\theta - (1-\gamma\theta)^2\Pi^2\right)^2}\right] s. \end{aligned}$$

Since $\beta_\theta > \beta_L$, this expression is strictly positive, implying that PP makes consumers better-off.

In the intermediate protection case, we need to compare $\overline{S}_F$ (consumers' surplus under the CF system) and S_{NF} (consumers' surplus under the PP system). Now,

$$\begin{aligned} S_{NF} - \overline{S}_F &= \frac{(\pi_{yn} - \pi_{nn}) r (r+\Pi)^2 \left(\beta_\theta - \beta_H (1-\gamma\theta)\right) (s_{yn} - s_{nn})}{\left(r^2\beta_\theta - (1-\gamma\theta)^2\Pi^2\right)\left(r^2\beta_H - \Pi^2\right)} \\ &+ (\pi_{yn} - \pi_{nn})^2 (r+\Pi) \left[\frac{r\beta_H + \Pi}{(r^2\beta_H - \Pi^2)^2} - \frac{(1-\gamma\theta)^2 \left(r\beta_\theta + (1-\gamma\theta)^2\Pi\right)}{\left(r^2\beta_\theta - (1-\gamma\theta)^2\Pi^2\right)\left(r^2\beta_H - \Pi^2\right)}\right] s. \end{aligned} \tag{18}$$

Recalling that in the intermediate protection case, $\gamma \geq (1 - \sqrt{\beta_\theta/\beta_H})/\theta$, we get $\beta_\theta - \beta_H(1-\gamma\theta)^2 \geq 0$, so the first line of (18) is positive. The square bracketed expression in the second line is increasing with γ and it vanishes at $\gamma = (1 - \sqrt{\beta_\theta/\beta_H})/\theta$; hence the second line is positive as well, so $S_{NF} > \overline{S}_F$ for all parameter values in the intermediate protection case. Finally, it is straightforward to establish that the first line of (18) is increasing with γ. Since the second line is also increasing with γ, it follows that the gain of consumers from PP is larger the larger is γ. ■

Proof of Proposition 6: (i) Since in the strong protection the CF system, $\overline{W}_F$, and under the PP system, W_F, differ only with respect to β, we can establish a sufficient condition for $W_F > \overline{W}_F$ by replacing β_θ with β in equation (10) and deriving a condition that ensures that $\partial\overline{W}_F/\partial\beta < 0$ for all $\beta \in [\beta_L, \beta_\theta]$. From equation (10),

$$\begin{aligned} \frac{\partial\overline{W}_F}{\partial\beta} &= -\frac{(\pi_{yn} - \pi_{nn}) r (1-\gamma\theta)^2 (r+\Pi)}{2\left(r^2\beta - (1-\gamma\theta)^2\Pi^2\right)^3} \times \left[(\pi_{yn} - \pi_{nn}) Z(r,\beta)\right. \\ &\left. + 2(\pi_{yn} - \pi_{nn}) M(\beta) S + 2(r+\Pi)\left(r^2\beta - (1-\gamma\beta)^2\Pi^2\right)(s_{yn} - s_{nn} + \pi_{ny} - \pi_{nn})\right], \end{aligned} \tag{19}$$

where

$$M(\beta) \equiv (r + (1-\gamma\theta)\Pi)^2 + r^2(\beta - 1) - 2r\gamma\theta(1-\gamma\theta)\Pi > 0,$$

and

$$Z(r,\beta) \equiv r^2\beta(r + 3\Pi) + (1-\gamma\theta)^2\Pi^2(3r + \Pi).$$

The expression outside the square brackets in (19) is negative inside the square brackets are positive (the last term is positive by Assumption A5). Hence $Z(r,\beta) \geq 0$ is sufficient for $\partial\overline{W}_F/\partial\beta < 0$ for all $\beta \in [\beta_L, \beta_\theta]$, which in turn ensures that $W_F > \overline{W}_F$. Now, surely,

$Z(r,\beta) > 0$ if $r + 3\Pi \geq 0$. Otherwise, $Z(r,\beta) \geq 0$ is sufficient for $Z(r,\beta) > 0$ for all $\beta \in [\beta_L, \beta_\theta)$. Recalling that $r > -\Pi$ and noting that $Z(r,\beta_\theta)$ is a convex function of r and that $Z'(-\Pi,\beta_\theta) < 0$ and $Z(-\Pi,\beta_\theta) < 0$, it follows that $Z(r,\beta_\theta) > 0$, provided that $r \geq \hat{r}(\beta_\theta)$, where $\hat{r}(\cdot)$ is defined in the proposition.

(ii) Recall that in the intermediate protection case, expected social welfare under the CF system is $\overline{W}_F$, and under the PP system, it is W_{NF}, where W_{NF} is equal to $\overline{W}_F$ when it is evaluated at $\theta = 0$. Since $\overline{W}_F$, and W_{NF} differ only with respect to θ, a sufficient condition for PP to enhance (lower) welfare is that $\partial\overline{W}_F/\partial\theta > 0$ ($\partial\overline{W}_F/\partial\theta < 0$) for all $\theta \in [0, \widehat{\gamma\theta}/\gamma)$. Using equation (10), we get

$$\begin{aligned}\frac{\partial\overline{W}_F}{\partial\theta} &= \frac{(\pi_{yn} - \pi_{nn} r(1-\gamma\theta)(r+\Pi)\left(\beta_H - \beta_M - \gamma(\beta_H + \beta_\theta)\right)}{2\left(r^2\beta_\theta - (1-\gamma\theta)^2\Pi\right)^2} \times \left[(\pi_{yn} - \pi_{nn} Z(r,\beta_\theta)\right. \\ &\quad \left. + 2(\pi_{yn} - \pi_{nn})M(\beta_\theta)s + 2(r+\Pi)\left(r^2\beta_\theta - (1-\gamma\theta)^2\Pi^2\right)\left(s_{yn} - s_{nn} + \pi_{ny} - \pi_{nn}\right)\right].\end{aligned}$$

To determine the sign of the derivative, note that the expression inside the square brackets is similar to the expression inside the square brackets in (19), and hence is positive when $r \geq \hat{r}(\beta_\theta)$. In that case, the sign of the derivative depends on the sign of $(\beta_H - \beta_M) - \gamma(\beta_H + \beta_\theta)$.

Finally, note that W_{NF} is independent of γ, while using equation (10),

$$\begin{aligned}\frac{\partial\overline{W}_F}{\partial\gamma} &= -\frac{(\pi_{yn} - \pi_{nn} r\beta_\theta(1-\gamma\theta)(r+\Pi)}{\left(r^2\beta - (1-\gamma\theta)^2\Pi^2\right)^3} \times \left[(\pi_{yn} - \pi_{nn})Z(r,\beta)\right. \\ &\quad \left. + 2(\pi_{yn} - \pi_{nn})M(\beta_\theta)s + 2(r+\Pi)\left(r^2\beta_\theta - (1-\gamma\beta)^2\Pi^2\right)\left(s_{yn} - s_{nn} + \pi_{ny} - \pi_{nn}\right)\right].\end{aligned}$$

If $r \geq \hat{r}(\beta_\theta)$, then $\partial\overline{W}_F/\partial\gamma < 0$. Thus, if $W_{NF} > \overline{W}_F$ (PP is welfare-enhancing), the PP increase as γ increases. If on the other hand $W_{NF} < \overline{W}_F$ (PP is welfare-reducing), the welfare loss from PP becomes smaller as γ increases. ■

Proof of Proposition 8: Under the PP system, firm 1 files for patent if and only if $\gamma > (1 - \sqrt{\beta_L/\beta_H})/\theta$. As β_L falls, the right side of the inequality increases, so firm 1 files for a smaller set of parameters. If the inequality still holds, firm 1 files for a patent under both filing systems, so the impact of PP on expected social welfare is given by $W_F - \overline{W}_F$ (i.e., the difference between expected welfare under PP and under CF). To examine how β_L affects $W_F - \overline{W}_F$, note that $\overline{W}_F$ is independent of β_L, while equation (19) implies that if $r \geq \hat{r}(\beta_L)$, then $\partial W_F/\partial\beta_L < 0$. Hence, whenever $r \geq \hat{r}(\beta_L)$, lowering β_L boosts the welfare gain from PP. ■

Proof of Proposition 9: We first consider the strong protection case. Under the CF system, $B = \overline{B}_F$, where $\overline{B}_F$ is given by equation (11). Under the PP system, $B = B_F$, where B_F is identical to $\overline{B}_F$ except that β_L replaces β_θ. Thus, the effect of PP on the incentive to invest in the first phase of the R&D process depends on the sign of the following expression:

$$B_F - \overline{B}_F = -\frac{(\pi_{yn} - \pi_{nn})(\pi_{yn} + \pi_{nn} - 2\pi_{ny})r(r^2 - \Pi^2)(1-\gamma\theta)^2(\beta_\theta - \beta_L)}{4\left(r^2\beta_L - (1-\gamma\theta)^2\Pi^2\right)\left(r^2\beta_\theta - (1-\gamma\theta)^2\Pi^2\right)} < 0.$$

Straightforward calculation reveals that this expression increases with γ; hence PP weakens the incentive to invent, but less so as γ increases.

In the intermediate protection case, $B = B_{NF}$ under the PP system and $B = \overline{B}_F$ under the CF system. Hence, the effect of PP on the incentive to invent depends on the sign of the following expression:

$$B_{NF} - \overline{B}_F = \frac{(\pi_{yn} - \pi_{nn})(\pi_{yn} + \pi_{nn} - 2\pi_{ny})r(r^2 - \Pi^2)(\beta_H(1-\gamma\theta) - \beta_\theta)}{2\left(r^2\beta_H - \Pi^2\right)\left(r^2\beta_\theta - (1-\gamma\theta)^2\Pi^2\right)} < 0,$$

where the inequality sign follows because in the intermediate protection case, $\gamma \geq (1 - \sqrt{\beta_\theta/\beta_H})/\theta$ (see Section 5.2); this ensures in turn that $\beta_H(1-\gamma\theta)^2 - \beta_\theta \leq 0$. Hence, once again, PP weakens the incentives to invest in the first phase of the R&D process. However now, straightforward calculation reveals that $B_{NF} - \overline{B}_F$ decreases with γ so the negative impact of PP increases when γ increases. ■

8 References

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