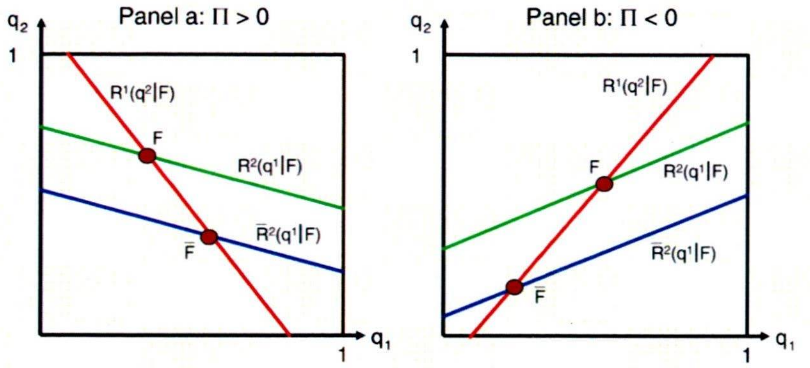

Fig. 3. Comparing the equilibrium in the filling subgame under the PP and the CF systems.

Lemma 1. *(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) $q_F^2 > \bar{q}_F^2$, $q_F^1 < \bar{q}_F^1$ *if* $\Pi > 0$, *and* $q_F^1 > \bar{q}_F^1$ *if* $\Pi < 0$,
(ii) $\pi_F^1 < \bar{\pi}_F^1$, *and* $\pi_F^2 > \bar{\pi}_F^2$ *if* $\Pi > 0$.

The intuition behind Lemma 1 is illustrated in Fig. 3. 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, $\bar{R}^2(q^1|F)$ lies below $R^2(q^1|F)$. Since the best-response function of firm 1, $R^1(q^2|F)$, is the same under the two systems, the equilibrium point under PP, F, is attained northwest of the equilibrium point under CF, $\bar{F}$, if $\Pi>0$ and northeast of $\bar{F}$ if $\Pi<0$. Part (ii) of Lemma 1 shows that firm 1 is worse-off filing for a patent under PP; intuitively this is because PP creates a larger technological spillover than CF. Part (ii) of the lemma also shows that whenever $\Pi>0$, firm 2 is better-off under PP. This is due not only to the larger technological spillover that firm 2 enjoys under PP, but also due to the fact that whenever $\Pi>0$, firm 1 invests less in R&D and is therefore less likely to bring the new technology to the product market. When $\Pi<0$, firm 1 invests more under PP so the overall effect of PP on firm 2 is ambiguous.

We are now ready to compare firm 1's propensity to file for a patent under the two systems.

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* $\gamma \le \hat{\gamma}$, *files for a patent under both systems if* $\gamma > \widehat{\gamma\theta}/\theta$, *and files for a patent only under the CF system if* $\hat{\gamma} < \gamma \le \widehat{\gamma\theta}/\theta$.

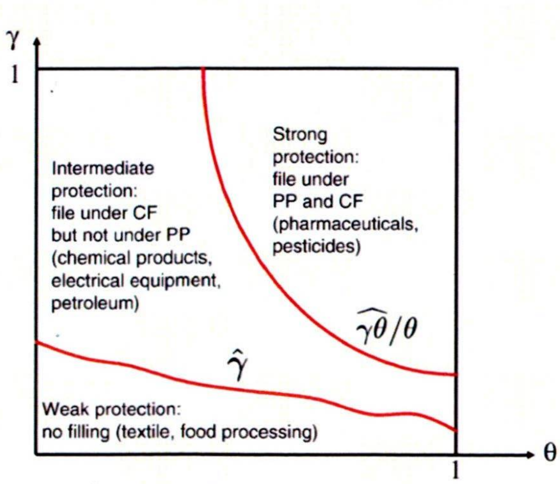

Fig. 4. Firm 1's filling decision under the PP and CF filling systems.

Proposition 3 is illustrated in Fig. 4 in the (θ, γ) space. When $\gamma \le \hat{\gamma}$, 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. Examples for industries with weak patent protection include some mature industries like textile, food processing, and fabricated metal products (Arundel and Kabla, 1998; Levin et al., 1987). When $\gamma > \widehat{\gamma\theta}/\theta$ patents receive strong protection since they are likely to be upheld in court; hence, firm 1 files for a patent under both filing systems. Examples for industries where patents are regarded as providing strong protection include pharmaceuticals, organic chemicals, and pesticides (Arundel and Kabla, 1998; Levin et al., 1987; Mansfield, 1986). Finally, when $\hat{\gamma} \le \gamma \le \widehat{\gamma\theta}/\theta$, 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 alternatives 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).

Proposition 3 has at least three important implications for PP which are now stated in the following corollaries. 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." Proposition 3 qualifies

[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.

this argument by suggesting that this adverse effect of PP pertains only to industries in which patent protection is intermediate.

Corollary 2. *When patent protection is strong, PP leads to an increase in q^2 and a decrease (increase) in q^1 if $\Pi>0$ ($\Pi<0$). When patent protection is intermediate and $\gamma\theta \geq 1-\frac{\beta_\theta}{\beta_H}$, PP leads to a decrease in q^2 and an increase (decrease) in q^1 if $\Pi>0$ ($\Pi<0$). If $\gamma\theta < 1-\frac{\beta_\theta}{\beta_H}$, then PP has an ambiguous effect on q^1 and q^2.*

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. Corollary 2 shows that on a theoretical ground, PP has an ambiguous effect on investments in R&D. Tepperman also finds that following the reform, firms have increased their patenting intensity. Although this finding is inconsistent with Corollary 1, one should bear in mind that Tepperman examines the combined effect of a switch from CF to PP and from first-to-invent to first-to-file, whereas we only examine the effect of a switch from CF to PP.[16]

Corollary 3. *PP hurts firm 1 when patent protection is strong or intermediate but it may benefit firm 2.*

When patent protection is weak, firm 1 does not file for a patent so PP is irrelevant. When patent protection is strong, firm 1 files for a patent under both systems, but PP hurts it because it leads to a larger technological spillover. PP also hurts firm 1 when patent protection is intermediate, because then firm 1 chooses to file for a patent only under the CF system. Since π_{NF}^1 is the same under the PP and CF systems, it follows from revealed preferences that firm 1's choice to file under the CF system means that it must be better-off than under the PP system. 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.

In the context of our model, it is natural to assume that small inventors will mainly play the role of firm 1, because they often lack the capacity and resources needed to absorb the technological spillovers generated by other firms. Corollary 3 may then explain 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.

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 the following assumption:

A3. $C(q)=rq^2/2$, where $r>\Pi$.

16 Scotchmer and Green (1990) show that firms have stronger incentives to invest in R&D and to file for patents under the first-to-file rule than under the first-to-patent rule. This result can explain Tepperman's findings.

Given Assumption A3, it is straightforward to show that the equilibrium levels of investment in the filing subgame under the PP system are

$$q_F^1=\frac{\left(\pi_{yn}-\pi_{nn}\right)\left(r\beta_L-(1-\gamma\theta)^2\Pi\right)}{r^2\beta_L-(1-\gamma\theta)^2\Pi^2},\quad q_F^2=\frac{\left(\pi_{yn}-\pi_{nn}\right)(1-\gamma\theta)(r-\Pi)}{r^2\beta_L-(1-\gamma\theta)^2\Pi^2}. \tag{6}$$

The corresponding levels of investment under the CF system, $\bar{q}_F^1$ and $\bar{q}_F^2$, are similar except that β_θ replaces β_L. In the no-fling subgame, the equilibrium levels of investment, q_{NF}^1 and q_{NF}^2, are also given by Eq. (6), with $\theta=0$ and with β_H replacing β_L. By Assumption A3, $r>\Pi$; together with the assumption that $\beta_\theta\geq\beta_L>1\geq 1-\gamma\theta$, this ensures that the equilibrium investment levels are all strictly between 0 and 1.

Substituting the equilibrium levels of investment into Eqs. (1) and (5) and recalling from Propositions 1 and 2 that $\widehat{\gamma\theta}$ is implicitly defined by $\pi_F^1=\pi_{NF}^1$ and $\hat{\gamma}$ is implicitly defined by $\bar{\pi}_F^1=\pi_{NF}^1$, we can establish the following result:

Lemma 2. Given Assumption A3, patent protection is:

(i) strong if $\gamma\geq\widehat{\gamma\theta}/\theta\equiv\frac{1-\sqrt{\beta_L/\beta_H}}{\theta}$,
(ii) intermediate if $\hat{\gamma}\equiv\frac{1-\sqrt{\beta_\theta/\beta_H}}{\theta}\leq\gamma<\frac{1-\sqrt{\beta_L/\beta_H}}{\theta}$,
(iii) weak if $\gamma<\frac{1-\sqrt{\beta_\theta/\beta_H}}{\theta}$.

In addition to Assumption A3, we also make the following assumptions:

A4. $s_{yy}\geq s_{yn}\geq s_{nn}$, $s_{yy}-s_{yn}\geq s_{yn}-s_{nn}>\pi_{nn}-\pi_{ny}$.

A5. $w_{yy}\geq w_{yn}\geq w_{nm}$.

Assumption A4 implies that the net present value of consumer surplus is increasing with the number of firms that use the new technology at an increasing rate. It also implies that the welfare gain to consumers when only one firm uses the new technology outweighs the associated loss to the firm that does not use the new technology. Assumption A5 implies that social welfare is increasing with the number of firms that use the new technology. Both assumptions hold in a broad class of oligopoly models; for instance, when the new technology is cost reducing, Assumptions A4 and A5 hold in the Cournot model with homogeneous products and a linear demand and in the Bertrand model with linear cost functions.

5.2.1. 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 systems when firm 1 files for a patent is,

$$\begin{aligned}S\left(q^1,q^2|F\right)&=q^1q^2(1-\gamma\theta)s_{yy}+\left(1-q^1\right)\left(1-q^2(1-\gamma\theta)\right)s_{nn}\\&\quad+\left[q^1\left(1-q^2(1-\gamma\theta)\right)+\left(1-q^1\right)q^2(1-\gamma\theta)\right]s_{yn}.\end{aligned} \tag{7}$$

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

$$S\left(q^1,q^2|NF\right)=q^1q^2s_{yy}+\left(1-q^1\right)\left(1-q^2\right)s_{nn}+\left[q^1\left(1-q^2\right)+\left(1-q^1\right)q^2\right]s_{yn}. \tag{8}$$

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 $\bar{S}_F\equiv S(\bar{q}_F^1,\bar{q}_F^2|F)$ 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 $\bar{S}_F$. Substituting for q_F^1 and q_F^2 from Eqs. (6) into (7) yields

$$S_F = s_{nn} + \frac{\left(\pi_{yn}-\pi_{nn}\right)^2(1-\gamma\theta)^2(r-\Pi)\left(r\beta_L-(1-\gamma\theta)^2\Pi\right)s}{(r^2\beta_L-(1-\gamma\theta)^2\Pi^2)^2} + \frac{\left(\pi_{yn}-\pi_{nn}\right)\left(r\beta_L+(1-\gamma\theta)^2(r-2\Pi)\right)\left(s_{yn}-s_{nn}\right)}{r^2\beta_L-(1-\gamma\theta)^2\Pi^2}, \tag{9}$$

where $s \equiv s_{yy}+s_{nn}-2s_{yn}>0$ by Assumption A4. The expression for $\bar{S}_F$ is identical, except that β_θ replaces β_L.

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 $\bar{S}_F$ and S_{NF}, where S_{NF} is also given by Eq. (9) when it is evaluated at $\gamma\theta=0$ and with β_H replacing β_L.

Proposition 4. *(The effect of PP on consumers.) Suppose that* Assumptions A3 and A4 *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 ($\gamma \geq \frac{1-\sqrt{\beta_L/\beta_H}}{\theta}$), firm 1 files for a patent under both filing systems. As Lemma 1 shows, PP induces both firms to invest more if $\Pi<0$, so consumers are better-off as the new technology is more likely to reach the product market. When $\Pi>0$, PP induces firm 2 to invest more and induces firm 1 to invest less. Given Assumption A3, the former effect dominates, so once again consumers are better-off under PP. Things are more subtle when patent protection is intermediate ($\frac{1-\sqrt{\beta_\theta/\beta_H}}{\theta} \leq \gamma < \frac{1-\sqrt{\beta_L/\beta_H}}{\theta}$), because then firm 1 files for a patent only under the CF system. As γ increases, patents are more likely to be upheld in court, so firm 1 is more likely to block firm 2 from using the new technology in the product market; hence, consumer surplus under the CF system, $\bar{S}_F$, decreases with γ. Under the PP system, firm 1 does not file for a patent, so the resulting consumer surplus, S_{NF}, is independent of γ. Noting that $\bar{S}_F = S_{NF}$ when $\gamma = \left(1-\sqrt{\beta_\theta/\beta_H}\right)/\theta$, it follows that $S_{NF} > \bar{S}_F$, and moreover, $S_{NF}-\bar{S}_F$ is increasing with γ.

5.2.2. Expected social welfare

Holding firm 1's interim R&D knowledge constant across the two filing systems, the (ex post) expected social welfare when firm 1 files for a patent is $W_F = S_F + \pi_F^1 + \pi_F^2$ under the PP system, and $\bar{W}_F = \bar{S}_F + \bar{\pi}_F^1 + \bar{\pi}_F^2$ under the CF system. When firm 1 does not file for a patent, the (ex-post) expected social welfare is $W_{NF} = S_{NF} + \pi_{NF}^1 + \pi_{NF}^2$. When patent protection is strong, firm 1 files for a patent under both systems, so the equilibrium expected social welfare is W_F under PP and $\bar{W}_F$ under CF. Given Assumption A3 and using Eqs. (1), (2), (6), and (9),

$$W_F = w_{nn} + \frac{\left(\pi_{yn}-\pi_{nn}\right)^2(1-\gamma\theta)^2(r-\Pi)\left(r\beta_L-(1-\gamma\theta)^2\Pi\right)s}{(r^2\beta_L-(1-\gamma\theta)^2\Pi^2)^2} + \frac{\left(\pi_{yn}-\pi_{nn}\right)\left(r\beta_L+(1-\gamma\theta)^2(r-2\Pi)\right)\left(s_{yn}-s_{nn}+\pi_{ny}-\pi_{nn}\right)}{r^2\beta_L-(1-\gamma\theta)^2\Pi^2} + \frac{\left(\pi_{yn}-\pi_{nn}\right)^2 r\left(\left(r\beta_L-(1-\gamma\theta)^2\Pi\right)^2+\beta_L(1-\gamma\theta)^2(r-\Pi)^2\right)}{2(r^2\beta_L-(1-\gamma\theta)^2\Pi^2)^2}. \tag{10}$$

The expression for $\bar{W}_F$ is identical except that β_θ replaces β_L.

In the intermediate protection case, firm 1 files for a patent only under the CF system, so the equilibrium expected social welfare is $\bar{W}_F$ under CF and W_{NF} under PP, where W_{NF} is identical to W_F except that $\gamma\theta=0$ and β_H replaces β_L.

Proposition 5. *(The welfare implications of PP.) Suppose that* Assumptions A3–A5 *hold and let*

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

Then,

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

Proposition 5 reveals that the welfare effect of PP depends on r, which measures the slope of the marginal cost of R&D. Intuitively, the R&D cost functions are convex; hence, all else equal, a more even allocation of investments between the two firms generates an efficiency gain which increases with r. When patent protection is intermediate, things also depend on γ, which is the likelihood that firm 1's patent is upheld in court. As γ increases, firm 2 becomes less likely to use the new technology and this lowers expected social welfare under the CF system, where firm 1 files for a patent. Under PP, 1 does not file for a patent so there is no similar negative effect.

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 an earlier PP leads to a drop in β_L by generating a larger technological spillover when firm 1 files for a patent.

Proposition 6. *(The effect of cutting the time between the filing date and the publication date.) Suppose that* Assumptions A3–A5 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, conditional on filing for a patent, grows larger.*

Proposition 6 shows that earlier publication of patent applications 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 effect 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.

6. Ex post licensing

So far we have assumed that when firm 1 holds a patent, it always sues firm 2 for patent infringement when firm 2 develops the new technology. In this section we relax this assumption. Assuming that $\pi_{yn}+\pi_{ny}>2\pi_{yy}$, firm 1 will continue to sue firm 2 for patent infringement when both firms manage to develop the new technology because the joint payoff when firm 1 wins in court, $\pi_{yn}+\pi_{ny}$, exceeds the joint payoff when firm 1 does not sue, $2\pi_{yy}$.[17]

Things are different however when firm 1 fails to develop the new technology, while firm 2 succeeds. In that case firm 1 can issue firm 2 an (ex post) license, which ensures that it will not sue firm 2; in return, firm 2 pays firm 1 a license fee. The resulting joint payoff of the two firms is then $\pi_{yn}+\pi_{ny}$. Without ex post licensing, firm 1 sues firm 2 and with probability γ it wins in court and prevents firm 2 from using the new technology. The resulting joint payoff of the two firms is then $2\pi_{nn}$. With probability $1-\gamma$, firm 2 wins in court and is then free to use the new technology, so the joint payoff of the two firms is $\pi_{yn}+\pi_{ny}$, exactly as in the case of ex post licensing. Comparing the joint payoff of the two firms under ex post licensing, $\pi_{yn}+\pi_{ny}$, with their joint payoff absent ex post licensing, $2\gamma\pi_{nn}+(1-\gamma)(\pi_{yn}+\pi_{ny})$, reveals that ex post licensing is efficient and generates an expected surplus of $\gamma(\pi_{yn}+\pi_{ny}-2\pi_{nn})$.

To examine the implications of ex post licensing, suppose that firms 1 and 2 divide the expected surplus from ex post licensing, $\gamma(\pi_{yn}+\pi_{ny}-2\pi_{nn})$, between them in proportions α and $1-\alpha$. Moreover, note that ex post licensing matters only when firm 1 files for a patent, a patent is granted, firm 1 fails to develop the new technology, and firm 2 succeeds. The probability of this event is $\theta(1-q^1)q^2$. Hence, ex post licensing increases the expected payoffs of firms 1 and 2 in the filing subgame by

$$\Delta\pi^1\left(q^1,q^2|F\right)=\theta\left(1-q^1\right)q^2\alpha\gamma\left(\pi_{yn}+\pi_{ny}-2\pi_{nn}\right),$$

and

$$\Delta\pi^2\left(q^1,q^2|F\right)=\theta\left(1-q^1\right)q^2(1-\alpha)\gamma\left(\pi_{yn}+\pi_{ny}-2\pi_{nn}\right).$$

Two observations are now immediate. First, $\Delta\pi^1(q^1,q^2|F)>0$, so ex post licensing has a direct positive effect on firm 1's payoff when it files for a patent. Second, $\Delta\pi^1(q^1,q^2|F)$ falls with q^1, while $\Delta\pi^2(q^1,q^2|F)$ increases with q^2, so the best-response function of firm 1 in the filing subgame (under both PP and CF) shifts inward, while the best-response function of firm 2 shifts outward. Since $\pi_{yn}+\pi_{ny}>2\pi_{yy}>\pi_{yy}+\pi_{nn}$, the best-response functions of the two firms are strategic substitutes ($\Pi>0$). Consequently, ex post licensing induces firm 1 to invest less in R&D in the filing subgame, and it induces firm 2 to invest more. Since this indirect effect lowers the equilibrium profit of firm 1 in the filing subgame, the overall effect of ex post licensing on firm 1's incentive to file for a patent is in general ambiguous. Nonetheless, given that the direct and indirect effects of ex post licensing on firm 1's payoff are the same under the PP and CF systems, ex post licensing does not affect the main qualitative conclusions of our analysis.

7. The incentives to accumulate interim R&D knowledge

Up to this point, we have focused on the implications of PP after firm 1 has already accumulated enough interim knowledge to file for a patent. In this section we ask how PP affects the firms' incentives to accumulate interim R&D knowledge in the first place. 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 accumulate interim R&D knowledge. As before, we only need to study the strong and intermediate protection cases because PP is irrelevant when patent protection is weak.

[17] The assumption that $\pi_{yn}+\pi_{ny}>2\pi_{yy}$ holds trivially when firms 1 and 2 are Bertrand competitors with linear cost functions and the new technology is cost-reducing, because then $\pi_{yn}>0=\pi_{yy}=\pi_{nn}=\pi_{ny}$. Likewise, this assumption holds when firms 1 and 2 are Cournot competitors with linear demand and cost functions and the new technology is sufficiently cost reducing. 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 $\pi_{ny}=(A-2k)^2/9$, so $\pi_{yn}+\pi_{ny}>2\pi_{yy}$ provided that $k>2A/5$.

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 $B=\bar{B}_F\equiv\bar{\pi}_F^1-\bar{\pi}_F^2$ under the CF system. Hence, the effect of PP depends on the sign of $B_F-\bar{B}_F$. By Lemma 1, when $\Pi>0$, then $\pi_F^1<\bar{\pi}_F^1$ and $\pi_F^2>\bar{\pi}_F^2$, so it is clear that $B_F<\bar{B}_F$. When $\Pi<0$, the relationship between π_F^2 and $\bar{\pi}_F^2$ is in general ambiguous. To examine the sign of $B_F-\bar{B}_F$, we therefore impose Assumption A3. Using Eqs. (1), (2), and (6),

$$B_F=\frac{\left(\pi_{yn}-\pi_{nn}\right)\left(\pi_{yn}+\pi_{nn}-2\pi_{ny}\right)r\left(\beta_L-(1-\gamma\theta)^2\right)}{2\left(r^2\beta_L-(1-\gamma\theta)^2\Pi^2\right)}. \tag{11}$$

$\bar{B}_F$ is given by the same expression except that β_θ replaces β_L.

When protection is intermediate, PP induces firm 1 to stop filing for a patent, so $B=B_{NF}\equiv\pi_{NF}^1-\pi_{NF}^2$. Under CF, firm 1 continues to file for a patent, so as before, $B=\bar{B}_F$. The effect of PP, then, depends on the sign of $B_{NF}-\bar{B}_F$, where B_{NF} is given by Eq. (11) with β_H replacing β_L and with $\theta=0$.

Proposition 7. *(The effect of PP on the incentives to accumulate interim R&D knowledge.) Given Assumption A3, PP weakens the incentive to accumulate R&D knowledge both when patent protection is strong and when it is intermediate. 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.*

Proposition 7 supports the concern 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 accumulate interim knowledge 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 $\bar{B}_F$) increases.

8. Conclusion

We have studied a cumulative innovation model in which one firm has accumulated interim R&D knowledge and needs to decide whether or not to apply for a patent. The benefit from applying is that if a patent is granted, the firm can sue its rival for patent infringement in case the rival successfully develops a new commercial technology. Applying for a patent is costly however because it creates a technological spillover which diminishes the technological advantage of the applicant. This spillover is larger under a PP system because then the rival gets access to the applicant's knowledge through the patent application (even if eventually the application 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.

Our results suggest that PP discourages patent applications in industries in which patent protection is intermediate and may weaken the incentives to invent. At the same time, holding the number of inventions fixed, PP may raise the likelihood that new technologies will reach the product market and may therefore benefit consumers and may also enhance social welfare.

Although our model is 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 briefly mention three possible extensions. First, in a dynamic model of R&D in which firms continuously accumulate interim R&D knowledge, firms need to decide not only whether to apply for a patent but also when to do it. Filing early is risky because the application is less likely to be accepted; on the other hand, an early filing contains less knowledge and hence leads to a smaller technological spillover. Applying early can also play a defensive role because the firm is not only able to sue rivals earlier, but can also preempt rivals from getting their own patent. This ensures that the firm will not be sued for patent infringement by rivals.

Second, it is possible to extend our analysis by allowing firm 1 to strategically decide how much interim knowledge to include in its patent application: including more knowledge increases the probability that a patent will be granted but also increases the degree of technological spillover.

Third, when firms have private information regarding the extent of their interim R&D knowledge (or even the fact that they are trying to develop the new technology), PP reveals this information to rivals earlier and for sure. This will obviously affect the incentives to file. Moreover, firms may 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. At the same time, PP may eliminate "submarine" patents, by giving firms a due warning about patent applications which are in the pipeline.[18]

Appendix A

Following are Lemma A1, and the proofs of Lemmas 1–2, Propositions 1–7, and Corollaries 2–3.

Lemma A1. *The effect of patent protection on the equilibrium R&D investments under the two filing systems:*

(i) $\frac{\partial q_F^2}{\partial(\gamma\theta)} < 0$ while the sign of $\frac{\partial q_F^1}{\partial(\gamma\theta)}$ *is equal to the sign of* Π. *Moreover,* $q_F^2 > q_{NF}^2$ *when* $\gamma\theta = 0$ *and conversely when* $\gamma\theta = 1 - \beta_L/\beta_H$.

(ii) $\frac{\partial \bar{q}_F^2}{\partial \gamma} < 0$ *while the sign of* $\frac{\partial \bar{q}_F^1}{\partial \gamma}$ *is equal to the sign of* Π. *Moreover,* $\bar{q}_F^2 > q_{NF}^2$ *when* $\gamma = 0$ *and conversely when* $\gamma = (1 - \beta_\theta/\beta_H)/\theta$.

Proof of Lemma A1.

(i) The Nash equilibrium in the filing subgame is implicitly defined by the equations $\frac{\partial \pi^1(q^1, q^2|F)}{\partial q^1} = 0$ and $\frac{\partial \pi^2(q^1, q^2|F)}{\partial q^2} = 0$. Differentiating this system with respect to $\gamma\theta$ yields:

$$\frac{\partial q_F^1}{\partial(\gamma\theta)} = \frac{\Pi\left[(1-\gamma\theta)\left[q_F^1\left(\pi_{yy} - \pi_{ny}\right) + \left(1 - q_F^1\right)\left(\pi_{yn} - \pi_{nn}\right)\right] + \beta_L q_F^2 C''\left(q_F^2\right)\right]}{\beta_L C''(q_F^1)C''(q_F^2) - \Pi^2(1-\gamma\theta)^2},$$

and

$$\frac{\partial q_F^2}{\partial(\gamma\theta)} = \frac{-\Pi^2(1-\gamma\theta)q_F^2 - \left[q_F^1\left(\pi_{yy} - \pi_{ny}\right) + \left(1 - q_F^1\right)\left(\pi_{yn} - \pi_{nn}\right)\right]C''\left(q_F^1\right)}{\beta_L C''(q_F^1)C''(q_F^2) - \Pi^2(1-\gamma\theta)^2},$$

where $\Pi \equiv \pi_{yn} + \pi_{ny} - \pi_{yy} - \pi_{nn}$. By Assumption A2, $C''(q_F^1)C''(q_F^2) > \Pi^2$; together with the fact that $\beta_L > 1$, it follows that the denominator in both expressions is strictly positive. Hence, $\frac{\partial q_F^2}{\partial(\gamma\theta)} < 0$ while the sign of $\frac{\partial q_F^1}{\partial(\gamma\theta)}$ is equal to the sign of Π.

To compare q_F^2 and q_{NF}^2, suppose first that $\gamma\theta = 0$. Then, Eqs. (1) and (3) coincide, so $R^1(q^2|F) = R^1(q^2|NF)$. On the other hand, since $\beta_L < \beta_H$, it follows that $R^2(q^1|F) > R^2(q^1|NF)$ for all q^1. Hence, $q_F^2 > q_{NF}^2$ (this is true irrespective or whether $\Pi > 0$ or $\Pi < 0$). Next, suppose that $\gamma\theta = 1 - \beta_L/\beta_H$. Then, it is easy to verify that $\frac{\partial \pi^2(q^1, q^2|F)}{\partial q^2} = 0$ implies $\frac{\partial \pi^2(q^1, q^2|NF)}{\partial q^2} = 0$, so $R^2(q^1|F) = R^2(q^1|NF)$. By contrast, $\frac{\partial^2 \pi^1(q^1, q^2|F)}{\partial q^1 \partial(\gamma\theta)} = q^2\Pi$, so $R^1(q^2|F) > R^1(q^2|NF)$ if $\Pi > 0$ and $R^1(q^2|F) < R^1(q^2|NF)$ if $\Pi < 0$. Recalling that the best-response functions are downward sloping when $\Pi > 0$ and upward sloping when $\Pi < 0$, it follows that $q_F^2 < q_{NF}^2$.

(ii) The proof is similar to the proof of part (i), except that β_θ replaces β_L and γ replaces $\theta\gamma$. □

Proof of Proposition 1. By Eq. (3), π_{NF}^1 is independent of γ and θ. Using the envelope theorem,

$$\frac{\partial \pi_F^1}{\partial(\gamma\theta)} = -q_F^2\left[q_F^1\left(\pi_{yy} - \pi_{yn}\right) + \left(1 - q_F^1\right)\left(\pi_{ny} - \pi_{nn}\right)\right] + \frac{\partial \pi_F^1}{\partial q^2}\frac{\partial q_F^2}{\partial(\gamma\theta)}. \quad (12)$$

Assumption A1 ensures that the bracketed expression and $\partial\pi_F^1/\partial q^2$ are negative. Since $\partial q_F^2/\partial(\gamma\theta) < 0$, it follows that $\partial\pi_F^1/\partial(\theta\gamma) > 0$.

To prove the existence of $\widehat{\gamma\theta} \in (0, 1 - \beta_L/\beta_H)$, such that $\pi_F^1 \gtreqless \pi_{NF}^1$ as $\gamma\theta \gtreqless \widehat{\gamma\theta}$, note that $\widehat{\gamma\theta}$ is defined implicitly $\pi_F^1 = \pi_{NF}^1$. Since π_F^1 increases with $\gamma\theta$, whereas π_{NF}^1 is independent of $\gamma\theta$, it suffices to show that $\pi_F^1 < \pi_{NF}^1$ if $\gamma\theta = 0$ and conversely if $\gamma\theta = 1 - \beta_L/\beta_H$. If $\gamma\theta = 0$, Eqs. (1) and (3) imply that $\pi^1(q^1, q^2|F) = \pi^1(q^1, q^2|NF)$. Consequently,

$$\pi_F^1 < \pi^1\left(q_F^1, q_{NF}^2|F\right) = \pi^1\left(q_F^1, q_{NF}^2|NF\right) \le \pi_{NF}^1,$$

where the strict inequality follows because $\partial\pi^1(q^1, q^2|F)/\partial q^2 < 0$ and since Lemma A1 states that $q_F^2 > q_{NF}^2$ 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 by Lemma A1, $q_F^2 < q_{NF}^2$. Using Eqs. (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 $\gamma\theta > 0$. Hence,

$$\pi_F^1 \ge \pi^1\left(q_{NF}^1, q_F^2|F\right) > \pi^1\left(q_{NF}^1, q_F^2|NF\right) > \pi_{NF}^1,$$

where the weak inequality is implied by revealed preferences and the second strict inequality follows because $\partial\pi^1(q^1, q^2|F)/\partial q^2 < 0$ and since $q_F^2 < q^2_{NF}$. □

Proof of Proposition 2. To prove the existence of $\hat{\gamma} \in (0, 1 - \beta_\theta/\beta_H)/\theta$, note that $\hat{\gamma}$ is defined implicitly $\bar{\pi}_F^1 = \pi_{NF}^1$. The proofs that $\bar{\pi}_F^1$ increases with γ and that $\bar{\pi}_F^1 < \pi_{NF}^1$ is similar to the proof of Proposition 1. Since π_{NF}^1 is independent of γ, it suffices to show that $\bar{\pi}_F^1 > \pi_{NF}^1$ if $\gamma = (1 - \beta_\theta/\beta_H)/\theta$. To this end, recall from Lemma A1 that $\bar{q}_F^2 < q_{NF}^2$ and recall from the proof of Proposition 1 that $\pi^1(q^1, q^2|F) > \pi^1(q^1, q^2|NF)$ for all $\gamma\theta > 0$. Consequently,

$$\bar{\pi}_F^1 \ge \bar{\pi}^1\left(q_{NF}^1, \bar{q}_F^2|F\right) > \pi^1\left(q_{NF}^1, \bar{q}_F^2|NF\right) > \pi_{NF}^1,$$

where the weak inequality is implied by revealed preferences and the second strict inequality follows because $\partial\pi^1(q^1, q^2|F)/\partial q^2 < 0$ and $\bar{q}_F^2 < q_{NF}^2$. □

Proof of Lemma 1.

(i) Follows immediately from Fig. 3.

(ii) Since $q_F^2 > \bar{q}_F^2$ and noting that $\partial\pi^1(q^1, q^2|F)/\partial q^2 < 0$,

$$\pi_F^1 < \pi^1\left(q_F^1, \bar{q}_F^2|F\right) \le \bar{\pi}_F^1,$$

where the weak inequality follows by revealed preferences.
As for firm 2, note that if $\Pi > 0$, then $q_F^1 < \bar{q}_F^1$. Together with the fact that $\partial\pi^2(q^1, q^2|F)/\partial q^1 < 0$, it follows that $\pi^2(q_F^1, \cdot|F) > \pi^2(\bar{q}_F^1, \cdot|F)$. Hence,

$$\pi_F^2 \ge \pi^2\left(q_F^1, \bar{q}_F^2|F\right) > \pi^2\left(\bar{q}_F^1, \bar{q}_F^2|F\right) > \bar{\pi}_F^2,$$

[18] Submarine patents refer to patent applications which are intentionally delayed by the applicants until a similar idea is commercialized by someone else, at which point the application is completed and entitles the patentholder to collect royalties. A case in point are the patents that were issued in the 1980s and the 1990s 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.

where the weak inequality follows from revealed preferences and the second strict inequality follows from Eqs. (2) and (4) by noting that $\beta_\theta > \beta_L$. □

Proof of Proposition 3. By Propositions 1 and 2, firm 1 files for a patent under the PP system if $\gamma > \widehat{\gamma\theta}/\theta$ and under the CF system if $\gamma > \hat{\gamma}$, where $\widehat{\gamma\theta}/\theta$ is defined implicitly by $\pi_F^1 = \pi_{NF}^1$ and $\hat{\gamma}$ is defined implicitly by $\bar{\pi}_F^1 = \pi_{NF}^1$. Since Propositions 1 and 2 show that $\frac{\partial \pi_F^1}{\partial \gamma}, \frac{\partial \bar{\pi}_F^1}{\partial \gamma} < 0$ and since $\pi_F^1 < \bar{\pi}_F^1$ by Lemma 1, it follows that $\hat{\gamma} < \gamma \leq \widehat{\gamma\theta}/\theta$. □

Proof of Corollary 2. When patent protection is strong, firm 1 files for a patent under both systems. The effect of PP on the R&D investments follows in this case from part (i) of Lemma 1. When patent protection is intermediate, firm 1 files for a patent only under the CF system. The R&D investment levels are then q_{NF}^1 and q_{NF}^2 under PP and $\bar{q}_F^1$ and $\bar{q}_F^2$ under CF. To compare these levels of investment, note that from Eqs. (4) and (5) that $R^2(q^1|NF)$ and $\bar{R}^2(q^1|F)$, respectively are implicitly defined by

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

and

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

Substituting from the $\frac{\partial \bar{\pi}^2(q^1,q^2|NF)}{\partial q^2} = 0$ into $\frac{\partial \bar{\pi}^2(q^1,q^2|F)}{\partial q^2}$ and rearranging terms,

$$\frac{\partial \bar{\pi}^2(q^1,q^2|F)}{\partial q^2} = \left[\left(1-\frac{\beta_\theta}{\beta_H}\right) - \gamma\theta\right]\beta_H C'\left(q^2\right).$$

If $\gamma\theta \geq 1-\frac{\beta_\theta}{\beta_H}$, then, evaluated at $q^2 = R^2(q^1|NF)$, $\frac{\partial \bar{\pi}^2(q^1,q^2|F)}{\partial q^2} \leq 0$, implying that $\bar{R}^2(q^1|F) \leq R^2(q^1|NF)$. If $\Pi > 0$, then $R^1(q^2|F) > \bar{R}^1(q^2|NF)$ and since the best-response functions are downward sloping, $\bar{q}_F^1 > q_{NF}^2$ and $\bar{q}_F^2 > q_{NF}^2$. If $\Pi < 0$, then $R^1(q^2|F) < R^1(q^2|NF)$ and since the best-response functions are upward sloping, $\bar{q}_F^1 < q_{NF}^2$ and $\bar{q}_F^2 < q_{NF}^2$. If $\gamma\theta < 1-\frac{\beta_\theta}{\beta_H}$, then, $\bar{R}^2(q^1|F) > R^2(q^1|NF)$ and hence the relationship between q_{NF}^1 and q_{NF}^2 and $\bar{q}_F^1$ and $\bar{q}_F^2$ is ambiguous. □

Proof of Corollary 3. The reason why PP hurts firm 1 is explained in the text following the proposition. To see that PP may benefit firm 2, suppose first that patent protection is strong. Then firm 1 files for a patent under both systems. Since $\beta_\theta > \beta_L$, it follows from Eqs. (2) and (4) that $\pi^2(q^1,q^2|F) > \bar{\pi}^2(q^1,q^2|F)$. Panel a of Fig. 3 shows that when $\Pi > 0$, $q_F^1 < \bar{q}_F^1$. Given that $\partial\pi^2(q^1,q^2|F)/\partial q^1 < 0$, this implies in turn that $\pi^2(q_F^1,\cdot|F) > \pi^2(\bar{q}_F^1,\cdot|F)$. Hence,

$$\pi_F^2 \geq \pi^2\left(q_F^1,\bar{q}_F^2|F\right) > \pi^2\left(\bar{q}_F^1,\bar{q}_F^2|F\right) > \bar{\pi}_F^2,$$

where the weak inequality follows from revealed preferences.

If patent protection is intermediate, then firm 1 files for a patent only under the CF system. Hence, we need to show that cases exist in which $\bar{\pi}_F^2 < \pi_{NF}^2$. Using Eqs. (4) and (5),

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

Substituting for the square bracketed term from the first order condition, $\frac{\partial \bar{\pi}^2(\bar{q}_F^1,\bar{q}_F^2|F)}{\partial q^2} = 0$, and recalling that $C(q)$ is strictly convex,

$$\pi^2\left(\bar{q}_F^1,\bar{q}_F^2|NF\right) - \bar{\pi}_F^2 = \frac{\theta\gamma\bar{q}_F^2\beta_\theta C'\left(\bar{q}_F^2\right)}{1-\gamma\theta} - \theta(\beta_H-\beta_M)C\left(\bar{q}_F^2\right)$$
$$> \frac{\theta\beta_H C\left(\bar{q}_F^2\right)}{1-\gamma\theta}\left[\gamma + 1 - \frac{\beta_M}{\beta_H})\right].$$

Hence, $\pi^2(\bar{q}_F^1,\bar{q}_F^2|NF) > \bar{\pi}_F^2$ for all $\gamma > 1-\beta_M/\beta_H$. If $q_{NF}^1 < \bar{q}_F^1$, then since $\partial\pi^2(q^1,q^2|NF)/\partial q^1 < 0$, it follows that

$$\pi_{NF}^2 \geq \pi^2\left(q_{NF}^1,\bar{q}_F^2|NF\right) > \pi^2\left(\bar{q}_F^1,\bar{q}_F^2|NF\right) > \bar{\pi}_F^2,$$

where the weak inequality follows by revealed preferences. □

Proof of Proposition 4. In the strong protection case, we need to compare $\bar{S}_F$ (consumers' surplus under the CF system) and S_F (consumers' surplus under the PP system). Now,

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

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 $\bar{S}_F$ (consumers' surplus under the CF system) and S_{NF} (consumers' surplus under the PP system). Now,

$$S_{NF} - \bar{S}_F = \frac{\left(\pi_{yn}-\pi_{nn}\right)r(r-\Pi)^2(\beta_\theta-\beta_H(1-\gamma\theta))\left(s_{yn}-s_{nn}\right)}{(r^2\beta_\theta-(1-\gamma\theta)^2\Pi^2)(r^2\beta_H-\Pi^2)}$$
$$+\left(\pi_{yn}-\pi_{nn}\right)^2(r-\Pi)\left[\frac{r\beta_H-\Pi}{(r^2\beta_H-\Pi^2)^2} - \frac{(1-\gamma\theta)^2\left(r\beta_\theta-(1-\gamma\theta)^2\Pi\right)}{(r^2\beta_\theta-(1-\gamma\theta)^2\Pi^2)(r^2\beta_H-\Pi^2)}\right]s. \tag{13}$$

Recalling that in the intermediate protection case, $\gamma \geq \left(1-\sqrt{\beta_\theta/\beta_H}\right)/\theta$, we get $\beta_\theta - \beta_H(1-\gamma\theta)^2 \geq 0$, so the first line of Eq. (13) is positive. The square bracketed expression in the second line is increasing with γ and it vanishes at $\gamma = \left(1-\sqrt{\beta_\theta/\beta_H}\right)/\theta$; hence the second line is positive as well, so $S_{NF} > \bar{S}_F$ for all parameter values in the intermediate protection case. Finally, it is straightforward to establish that the first line of Eq. (13) 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 5.

(i) In the strong protection case we need to compare W_F and $\bar{W}_F$. Noting that $\bar{W}_F$ is identical to W_F, expect that β_θ replaces β_L, we can show that $W_F > \bar{W}_F$ by establishing a sufficient condition for $\partial W_F/\partial\beta < 0$ for all $\beta \in [\beta_L, \beta_\theta]$. From Eq. (10),

$$\frac{\partial W_F}{\partial \beta} = -\frac{\left(\pi_{yn}-\pi_{nn}\right)r(1-\gamma\theta)^2(r-\Pi)}{2(r^2\beta-(1-\gamma\theta)^2\Pi^2)^3}$$
$$\times\left[\left(\pi_{yn}-\pi_{nn}\right)Z(r,\beta) + 2\left(\pi_{yn}-\pi_{nn}\right)M(\beta)S\right.$$
$$\left.+2(r-\Pi)\left(r^2\beta-(1-\gamma\beta)^2\Pi^2\right)\left(s_{yn}-s_{nn}+\pi_{ny}-\pi_{nn}\right)\right], \tag{14}$$

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 Eq. (14) is negative, while the last two expressions inside the square brackets are positive (the last term is positive by Assumption A4). Hence $Z(r, \beta) \geq 0$ is sufficient for $\partial W_F/\partial\beta < 0$ for all $\beta \in [\beta_L, \beta_\theta]$, which in turn ensures that $W_F > \bar{W}_F$. 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 from Assumption A3 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) When protection is intermediate, we need to compare W_{NF} and $\bar{W}_F$. Noting that $W_{NF} = \bar{W}_F$ when $\theta = 0$ (in that case $\beta_\theta = \beta_H$), a sufficient condition for PP to enhance (lower) welfare is that $\partial\bar{W}_F/\partial\theta < 0$ ($\partial\bar{W}_F/\partial\theta > 0$) for all $\theta \in \left[0, \widehat{\gamma\theta}/\gamma\right)$. Using Eq. (10),

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

The expression inside the square brackets is similar to the expression inside the square brackets in Eq. (14) and is therefore positive when $r \geq \hat{r}(\beta_\theta)$. In that case, the sign of $\frac{\partial \bar{W}_F}{\partial\theta}$ depends on the sign of $(\beta_H - \beta_M) - \gamma(\beta_H - \beta_\theta)$ which is negative (positive) if $\gamma > (<) \frac{\beta_H - \beta_M}{\beta_H + \beta_\theta}$.
Finally, note that W_{NF} is independent of γ, while using Eq. (10),

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

which is negative when $r \geq \hat{r}(\beta_\theta)$. Thus, W_{NF} does better relative to $\bar{W}_F$ as γ increases. □

Proof of Proposition 6. Under PP, firm 1 files for patent if $\gamma > \left(1 - \sqrt{\beta_L/\beta_H}\right)/\theta$. 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 welfare effect of PP is given by $W_F - \bar{W}_F$, where $\bar{W}_F$ is independent of β_L, while $\partial W_F/\partial\beta_L < 0$ if $r \geq \hat{r}(\beta_L)$ (see Eq. (10)). Hence, so long as $r \geq \hat{r}(\beta_L)$, lowering β_L boosts the welfare gain from PP. □

Proof of Proposition 7. In the strong protection case, the effect of PP on the incentive to accumulate interim R&D knowledge depends on the sign of the following expression:

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

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, the effect of PP depends on the sign of:

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

where the inequality follows because in the intermediate protection case, $\gamma \geq \left(1 - \sqrt{\beta_\theta/\beta_H}\right)/\theta$ (see Lemma 2), which ensures that $\beta_H(1 - \gamma\theta)^2 - \beta_\theta \leq 0$. Hence, once again, PP weakens the incentives to accumulate interim R&D knowledge. However now, straightforward calculation reveals that $B_{NF} - \bar{B}_F$ decreases with γ, so the negative impact of PP increases when γ increases. □

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Collective Rights Organizations and Investment in Upstream R&D

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Abstract

We examine third-party collective rights organisations (CROs) such as clearinghouses that license innovations on behalf of inventors when downstream uses require licenses to multiple complementary innovations. We consider two simple royalty redistribution schemes, two different innovation environments and two different antitrust rules. We show that in most cases CROs increase incentives to invest in R&D as they increase profits from licensing. However, incentives to invest of inventors who have the unique ability to develop a crucial component may be weakened. We also show that CROs may increase or decrease expected welfare, and are more likely to be beneficial when R&D costs are relatively high, and/or the probability of success for inventors is relatively low.

Keywords: Intellectual property, licensing, collective rights organizations, anticommons.

JEL: L24, O31, O34

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1 Introduction

Many new innovations or products depend on multiple complementary upstream intellectual property rights. When different upstream components have different owners, licensing for downstream uses that combine these components may suffer from various inefficiencies dubbed the "tragedy of the anticommons" (Heller & Eisenberg 1998, Buchanan & Yoon 2000). Specifically, negotiating with multiple licensors may entail high transaction costs, and independent uncoordinated licensors may set royalties that are inefficiently high in total. For example, development of a new medical genetic diagnostic test may require licensing multiple patented inventions, owned by different inventors, related to gene sequences, gene expression technologies, and so on (Van Overwalle *et al* 2006, OECD 2002). This may retard downstream innovation and/or lead to end-users paying high prices for downstream products. As well as genetics, similar situations can also arise in information technology and communications industries, for example (Shapiro 2001, Aoki & Nagaoka 2005).

In response to these licensing inefficiencies, a number of "collective rights" organizations (CROs) and arrangements have emerged or been promoted, including patent pools, cross-licensing, copyright collectives, and third-party clearinghouses (Shapiro 2001, van Zimmeren *et al* 2006, Aoki & Schiff 2008, Aoki, 2008) discusses various types of CROs (excluding clearinghouses) and how these may be used to mitigate anticommons problems in licensing. Patent pools in particular have received much attention in the literature, for example, Lerner & Tirole (2004) examine when patent pools are efficiency enhancing ex post, and Lerner *et al* (2007) empirically examine the types of licensing rules used by patent pools. Layne-Farrar & Lerner (2008) and Aoki & Nagaoka (2004) examine royalty distribution rules of patent pools and incentives of patent owners to join pools, which is are issues that also arises in the current paper. Hoppe and Ozdenoren (2005) examine the role of CROs as intermediaries to reduce informational problems in licensing markets. In contrast to our paper, all of these papers take an existing set of intellectual property rights as given. We concentrate on the effects of collective licensing on incentives to innovate. Most similar to our work is Gilbert & Katz (2007) and Meniere (2008) who consider division of profits among innovators who are racing to develop complementary components, however they do not examine collective licensing. In this paper we focus on the effects of CROs on incentives to invest in upstream R&D for complementary components and the consequences for economic welfare.

We use a simple product innovation framework where a downstream innovation or product requires the development of two complementary upstream components. A number of upstream research firms can invest in developing these components, and each has some probability of success. When multiple firms invest, there is some chance that multiple substitute versions of either or both components will be developed independently. All successful innovators earn revenues by licensing their innovations to downstream users. After research firms invest and the outcome of the innovation process is realized, each successful inventor can choose to license independently, or join a CRO that licenses on behalf of its members. The CRO sets a single royalty to maximize the joint profits of its members.

We evaluate several different modes of operation for the CRO relating to its royalty distribution scheme and antitrust policy. Antitrust policy either does or does not allow the CRO to license substitute innovations jointly. The CRO may also distribute royalty revenues equally or unequally among its members according to whether they are the sole inventor of a component or whether there are substitutes for a component. Ex post, we show that banning licensing of substitutes can generate the same welfare level as not banning but permitting the CRO to use an unequal redistribution rule. In addition, an unequal redistribution rule can perform better than an equal redistribution rule as it can ensure that sole inventors of a component do not prefer to license independently from the CRO. However, unless licensing of substitutes is banned, a CRO may reduce ex post welfare if both components have multiple substitutes.

In the long run, the effects of a CRO on the ex ante incentives of upstream innovators to invest are arguably more important than the ex post effects on licensing of existing innovations. We therefore consider two different innovation models within which we compare the ex ante performance of CROs. In the first model, both components are symmetric and a large number of competitive research firms have the ability to develop each. In the second model, one component is unique and a single firm has the ability to develop it while the other component has many possible inventors.

We find that CROs generally increase ex ante incentives to invest in upstream R&D, as the expected ex post profit gains from joint licensing outweigh any losses from royalty sharing. A possible exception is when one component can only be developed by one firm and the CRO is permitted to license substitutes jointly. In this case the unique inventor only benefits from the CRO if the other component has a single inventor, which occurs with relatively high probability only when investment in the other component is relatively low. Further, since the CRO increases ex post profits of inventors of substitute components, it increases investment in such components, and thus is more likely to make the unique inventor worse off.

CROs may also increase or decrease ex ante expected welfare. We show that a CRO that distributes royalties unequally can always generate higher expected welfare for a given level of investment than no CRO, as it can achieve participation of all successful innovators and solve the "anticommons" inefficiencies without introducing excessive anticompetitive distortions ex post. In the symmetric investment model, this means that an unequal CRO that can license substitutes jointly is equivalent to a CRO that is not permitted to license substitutes jointly. Thus unequal redistribution rules can replace antitrust rules without affecting welfare. In contrast, a CRO that distributes royalties equally and can license substitutes jointly does not always perform better than no CRO for a given investment level, as it cannot achieve full participation of innovators. We show that an equal CRO only performs better than no CRO when the level of investment in R&D is relatively low, so that the probability that one or both components has multiple successful inventors is not too high.

These basic welfare comparisons do not take account of the change in the R&D investment level induced by the CRO. Once investment is made endogenous, an unequal CRO or a CRO that cannot license substitutes jointly can reduce ex ante expected welfare if it causes an excessive increase in investment. We use a numerical simulation based on a binomial innovation process to compare the equilibrium expected welfare of the different CROs under the different innovation models. In general, a CRO that redistributes royalties unequally or a CRO that cannot license substitutes jointly performs better than one that distributes royalties equally and can license substitutes jointly, except for some relatively small subset of parameter values. In addition, the CROs tend to perform better than no CRO when costs of innovation are high, and/or the probability of an inventor's success is low, as these are the cases where stimulating R&D investment through increased licensing profits is most likely to be beneficial.

The organization of the rest of this paper is as follows. In the next section we present a simple model of ex post licensing with a CRO. Then in section 3 we embed this in two different upstream investment models, and compare different types of CRO in terms of ex ante expected profits and welfare. In section 4 we perform further welfare analysis using numerical simulations with endogenous investment. Section 5 concludes.

2 Effects of CROs on ex post licensing

Our model of IP licensing is as follows. There are two complementary components or research tools, A and B, that are needed for the production of a downstream innovation or product. Upstream research firms invest in R&D to develop these components and earn royalties by licensing their innovations to downstream users. An inventor of either component cannot earn any royalties unless the other component has also been invented. There are a large number of research firms, each of which has the capacity to undertake a single research 'project' at some cost. Research firms are specialized in the development of A or B. Any research project may result in the invention of one of the components or it may be unsuccessful and invent nothing. We allow for the possibility that perfect substitute versions of either component may be independently invented by different inventors.

A third-party CRO may also exist and can license innovations on behalf of member inventors. All successful inventors have the option to join the CRO or license independently. The CRO seeks to maximize the total royalty revenues of its members from licensing, and distributes these revenues among its members according to a distribution rule that it announces in advance. The CRO may also be subject to an antitrust rule that prohibits it from jointly licensing substitute innovations.

Definition 1 *The CRO operates under a* strict antitrust rule *if joint licensing of substitutes is prohibited.*

If a strict antitrust rule applies and substitute inventors of either component have joined the CRO, we assume that the downstream licensee picks one of the substitute versions at random to license and only the chosen version receives royalty payments. If the antitrust rule is not strict, joint licensing of substitute innovations is permitted and royalties are shared among all members.

Given this setup, innovation and licensing takes place in four stages:

Stage 1: The antitrust rule is set and announced.

Stage 2: The CRO sets and announces a royalty redistribution rule consistent with the anti-trust rule.

Stage 3: Each research firm decides whether or not to invest in an R&D project and those that invest invent a component according to their type, with some probability.

Stage 4: Successful inventors simultaneously decide whether or not to join the CRO or license independently, and then innovations are licensed by the CRO and/or any independent inventors and royalties are paid by licensees.

In this section we describe our model of the final (ex-post) stage of this process and find the ex post equilibrium payoffs of successful inventors and equilibrium welfare, for a given outcome of the earlier stages. The next section examines two alternative models of the third stage and compares different antitrust and redistribution rules.

We look for a subgame perfect equilibrium. Provided that both components have been invented, successful inventors can earn royalties from licensing. Let π_M denote the total monopoly royalties obtained by licensing all successful inventions of both components jointly and let π_D denote the duopoly royalties each component receives when there is one independent licensor for each component. Similarly, let W_M denote the total welfare level that arises when both components are licensed jointly, W_D denote the welfare level when the two components are licensed by two independent licensors, and $W_0 > W_M$ denote the welfare level when both components are licensed for zero royalties. Since components A and B are perfect complements, we make the following assumption about ex post profit and welfare levels:

Assumption 1 *The 'tragedy of the anticommons' reduces joint profits and welfare when the two components are licensed by two independent licensors compared to when they are licensed jointly:* $\pi_M \geq 2\pi_D$ *and* $W_M \geq W_D$.

The payoffs of successful inventors depend on the redistribution rule of the CRO and the antitrust rule. If the antitrust rule is strict, the CRO can license at most one innovation for each component. If it licenses innovations for both components, we assume the total royalties are shared equally between the two specific innovations chosen by the downstream user.

If the antitrust rule is not strict, the CRO licenses all the innovations of its members jointly and shares royalty revenues among all members. In this case we consider two different policies:

Definition 2 *An* equal CRO *distributes its royalty revenues equally among its members. If the CRO earns* π *and has* n *members, each member receives* π/n.

Definition 3 *An* unequal CRO *distributes disproportionate royalty revenues to a member (if any) who is the sole successful inventor of a component when the other component is competitive. If the CRO earns* π *and one component has a single inventor and the other component has* $n \geq 2$ *inventors, the monopoly inventor receives* $z\pi$ *and all other inventors receive* $(1-z)\,\pi/n$, *where* $z \in \left(\frac{1}{n+1}, 1\right)$. *In all other situations, the CRO distributes revenues equally among its members.*

There are three cases where downstream production is possible:

Case 'MM': Both components have a single successful inventor;

Case 'MC': One component has a single inventor and the other component has two or more substitute (competitive) inventors; and

Case 'CC': Both components have two or more substitute inventors.

In cases MC and CC, inventors of a competitive component cannot earn any royalties unless they all join a CRO, since competition between them will drive royalties down to zero. Thus such inventors always join the CRO, if it exists.

In cases MM and MC a monopoly inventor of a component may or may not want to join the CRO. In case MM, if both inventors license independently they each receive π_D, while if both join any type of CRO they receive $\pi_M/2$. If one inventor joins the CRO but the other does not, the situation is effectively the same as where both do not join, and both receive π_D. Therefore, by Assumption 1, both successful inventors have a weakly dominant strategy to join a CRO in case MM.

If case MC arises, the successful inventors of the competitive component will all join the CRO, as explained above. Suppose the competitive

CRO Type	π_{MM}	π_{MC}^{M}	$\pi_{MC}^{C}(n)$	$\pi_{CC}(n_A, n_B)$
None	π_D	π_M	0	0
Equal (not strict)	$\pi_M/2$	π_D	π_D/n	$\pi_M/(n_A+n_B)$
Unequal (not strict)	$\pi_M/2$	$z\pi_M$	$(1-z)\,\pi_M/n$	$\pi_M/(n_A+n_B)$
Strict	$\pi_M/2$	$\pi_M/2$	$\frac{1}{n}\pi_M/2$	$\frac{1}{n_i}\pi_M/2;\ i=A,B$

Table 1: Equilibrium payoffs of successful inventors under different types of CRO and different outcomes of the innovation process.

component has n inventors. Under a strict antitrust rule, the CRO can license at most one invention of the competitive component together with the sole invention of the other component. Thus the inventor of the monopoly component receives $\pi_M/2$ from joining the CRO and π_D from not joining, so the monopoly inventor will join. If the antitrust rule is not strict, the monopoly inventor will join an equal CRO if $\pi_M/(n+1) \geq \pi_D$ and will join an unequal CRO if $z\pi_M \geq \pi_D$. To differentiate equal and unequal CROs, we make the following assumption:

Assumption 2 *A monopoly inventor of a component does not join an equal CRO when there are $n \geq 2$ inventors of the other component, but does join an unequal CRO. That is, $\pi_M \leq 3\pi_D$ and $z \geq \pi_D/\pi_M$.*[1]

We can now summarize the equilibrium payoffs of successful inventors in stage 4, in each of the three ex post cases above. Let π_{MM} be the royalties that a successful inventor receives in case MM, let π_{MC}^{M} be the royalties that the monopoly inventor receives in case MC, let $\pi_{MC}^{C}(n)$ be the royalties that a successful inventor of the competitive component receives in case MC when there are $n \geq 2$ inventors of that component, and let $\pi_{CC}(n_A, n_B)$ be the royalties that a successful inventor receives in case CC when there are $n_A \geq 2$ and $n_B \geq 2$ successful inventors of A and B respectively.

Table 1 shows the values of these payoffs for different types of CRO. In comparison with no CRO, an equal CRO increases an inventor's royalties if there are multiple inventors of the same component, or if there is only one inventor of both components. However, such a CRO decreases royalties from π_M to π_D when the inventor is the sole inventor of a component but

[1] Such a value of z achieves the CRO's objective of maximising the total royalties of its members, since it ensures that the total CRO royalties are π_M.

the other component is competitive. In this situation, the existence of the CRO reduces competition among inventors of the competitive component, which benefits them but harms the sole inventor of the other component.

An unequal CRO increases a successful inventor's royalties compared to no CRO unless the inventor is the sole inventor of one component while the other component is competitive. In this case the value of z is sufficient to induce the monopoly inventor to join the CRO, but she is still worse off compared to when no CRO exists, because the CRO gives some fraction of π_M to the competitive inventors of the other component. An unequal CRO may also make successful inventors better or worse off compared to an equal CRO. If, for example, A has a single inventor but B is competitive, the inventors of B receive π_D/n_B under an equal CRO, but $(1-z)\,\pi_M/n_B$ under an unequal CRO. Since $z \geq \pi_D/\pi_M$ to attract the inventor of A to join the unequal CRO, this reduces the payoffs of the inventors of B relative to the equal CRO.

Finally, if the antitrust rule is strict, the CRO induces all inventors to join and total ex-post licensing revenues are π_M, which is the same outcome as an unequal CRO without a strict antitrust rule. From Table 1, a CRO under a strict antitrust rule makes all inventors better off compared to no CRO except the monopoly inventor in case MC (like an unequal CRO). In cases MC and CC, all inventors of the competitive components join the CRO, but only one is chosen by the downstream licensor. Thus competitive licensors receive a payoff of $\pi_M/2$ with probability $1/n_i$ where n_i is the number of inventors of the same component.

Similarly, let W_{MM}, W_{MC} and W_{CC} be the equilibrium welfare levels attained in the three ex-post cases where production is possible. Table 2 shows the welfare levels (ignoring R&D costs) that result under each type of CRO in each case. Compared to no CRO, an equal CRO improves welfare when both components have a single inventor (case MM), but reduces welfare in all other cases, as the CRO allows substitute inventors of the same component to reduce competition among themselves. An unequal CRO with an appropriate value of z always attracts all inventors to join, and thus always achieves the welfare level W_M. Compared to no CRO, this increases welfare in case MM, but reduces welfare when both components have multiple inventors (case CC), and leaves welfare unchanged in case MC. In every case an unequal CRO generates at least as much welfare as an equal CRO, and

CRO Type	$\mathbf{W}_{MM}$	$\mathbf{W}_{MC}$	$\mathbf{W}_{CC}$
None	W_D	W_M	W_0
Equal (not strict)	W_M	W_D	W_M
Unequal (not strict)	W_M	W_M	W_M
Strict	W_M	W_M	W_M

Table 2: Equilibrium ex-post welfare (ignoring sunk investment costs) from licensing under different types of CRO.

outperforms it in case MC. A CRO under a strict antitrust rule achieves the same ex-post outcome as an unequal CRO, as it always induces all successful inventors to join.

3 Effects of CROs on ex ante expected profits and welfare

In this section we examine and compare CROs under two alternative models of the innovation process.

3.1 Investment model 1: All research projects are equal

In this model, each research project costs c and has the same chance of developing a component or developing nothing. Research firms and projects are exogenously specialized towards the development of A or B and a large number of firms are capable of undertaking projects of each type. Let N_A and N_B be the total number of projects undertaken to develop A and B respectively. The success of any project is independent of that of any other project. Given that $N_i \geq 1$ projects are undertaken for component $i = A, B$, the probability that $n_i \leq N_i$ successfully develop the component is denoted by $P(n_i, N_i)$, where $\sum_{n_i=0}^{N_i} P(n_i, N_i) = 1$ and $\lim_{N_i \to \infty} P(n_i, N_i) = 0$ for all $n_i \in \{0, 1, ..., N_i\}$.

Since the components are identical, we consider symmetric situations where $N_A = N_B = N$, thus $2N$ projects are undertaken in total. The expected profit of a research firm given N is denoted $\pi(N)$. The probability of case MM and a given research firm is one of the successful ones is $\frac{1}{N} P(1, N)^2$. The probability that a research firm is the sole inventor of their component while the other component has $n \geq 2$ inventors (case MC, monopoly) is $\frac{1}{N}P(1,N)\,P(n,N)$. The probability that a research firm is one of $n \geq 2$ competitive inventors of their component in case MC is $\frac{n}{N}P(n,N)\,P(1,N)$. The probability that a research firm is one of $m \geq 2$ inventors of their component while the other component has $n \geq 2$ inventors (case CC) is $\frac{m}{N}P(m,N)\,P(n,N)$. Considering all possibilities under which the three cases can occur, using the payoff definitions from Table 1, the expected ex-ante profit of a research firm is

$$\begin{aligned}\pi(N) &= \tfrac{1}{N}P(1,N)^2\,\pi_{MM} + \tfrac{1}{N}P(1,N)\sum_{n=2}^{N}P(n,N)\left[\pi_{MC}^{M} + n\pi_{MC}^{C}(n)\right] \\ &\quad + \sum_{m=2}^{N}\sum_{n=2}^{N}\tfrac{m}{N}P(m,N)\,P(n,N)\,\pi_{CC}(m,n) - c. \qquad (1)\end{aligned}$$

First let us consider the effect of imposing the strict antitrust rule on the CRO. From Table 1, both the unequal CRO and a strict CRO generate total royalties of π_M, but the distribution of these royalties among successful inventors differs except in case MM. Let $\pi^{UC}(N)$ and $\pi^{SC}(N)$ denote the expected ex-ante profits of an inventor under an unequal CRO and a strict CRO respectively. Substituting the appropriate ex-post payoffs from Table 1 into (1), we obtain

$$\begin{aligned}\pi^{UC}(N) &= \frac{1}{N}\left[\frac{1}{2}P(1,N)^2 + P(1,N)\sum_{n=2}^{N}P(n,N)\right]\pi_M \\ &\quad + \frac{1}{N}\sum_{m=2}^{N}\sum_{n=2}^{N}\tfrac{m}{m+n}P(m,N)\,P(n,N)\,\pi_M - c \qquad (2)\end{aligned}$$

and

$$\begin{aligned}\pi^{SC}(N) &= \frac{1}{N}\left[\frac{1}{2}P(1,N)^2 + P(1,N)\sum_{n=2}^{N}P(n,N)\right]\pi_M \\ &\quad + \frac{1}{N}\sum_{m=2}^{N}\sum_{n=2}^{N}P(m,N)\,P(n,N)\,\frac{\pi_M}{2} - c. \qquad (3)\end{aligned}$$

Note that $\pi^{UC}(N)$ is independent of z, due to the symmetry of research projects. Comparing $\pi^{UC}(N)$ and $\pi^{SC}(N)$ gives the following result.