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Innovation in the shadow of patent litigation

Yann Ménière and Sarah Parlane*

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Abstract

We analyze non-cooperative R&D investment by two firms that already hold patents that they can assert against each other with probabilistic success. The market structure results from stochastic innovation and patent litigation. Depending on the level of infringement fees, we highlight positive and negative effects of litigation threats on innovation. We define an appropriate regulatory structure of infringement fees that will implement socially efficient R&D investments in the case of symmetric and asymmetric patent portfolios.

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1 Introduction

Patents are meant to create incentives to invest in R&D by conferring property rights, including legal exclusivity on innovations. Yet in some cases patents may also represent an impediment for innovators. As products embody increasing numbers of patented components, especially in sectors such as semiconductors and computer hardware and software, it is often difficult for an innovator to anticipate exactly what patents she might be infringing. Therefore innovators face a threat of patent litigation by other patent owners even though they did not knowingly imitate any patented technology.

The eBay v. MercExchange case in the U.S. illustrates the problem. MercExchange entered the online auction market in 1995, but failed commercially and exited in 2000. In the meantime it had filed minor patents for online auctions and for direct-buy software. The auction giant eBay had developed similar tools and therefore contacted MercExchange in 2000 to buy the patents. MercExchange refused and decided instead to sue eBay for infringement in 2001. Such litigation reallocates innovation profits between firms that engaged into similar technology paths ex ante. Therefore it affects incentives to innovate and affect R&D efficiency.

In practice patent owners generally seek an injunction when their patent covers a component of a larger product. An injunction allows the patent owner potentially to obtain much more than what the patented component is actually worth, because it allows the patent owner to hold-up the production and commercialization of the entire product until a settlement is reached (Lemley and

Shapiro, 2006). This use of an injunction is increasingly seen as detrimental to innovation (FTC, 2003; Lemley and Shapiro, 2006). The U.S. draft Patent Reform Act of 2005 aimed to limit access to injunctions, and called for a renewed definition of infringement penalties.¹ In this context, in May 2006 the U.S. Supreme Court overturned the Court of Appeals for the Federal Circuit decision to issue a permanent injunction against eBay. In July 2007 the District Court issued an order denying the injunction and ruling that monetary damages were a sufficient remedy in that case. In parallel, a Patent Reform bill is being considered in the Congress that would require that damages awarded more accurately reflect the actual harm caused by a patent infringement when the infringing product embodies a combination of several patented inventions.

In this paper, we study the interplay between hold-up litigation and investments in R&D, and propose a policy instrument to implement efficiency. We consider firms that develop innovations in the shadow of each other's patent portfolios. In the absence of litigation threats firms play a standard R&D race in which they tend to overinvest. But this over-investment can eventually reverse as the threat of patent litigation erodes the incentives to innovate. We use this setting to evaluate the efficiency of firms' investments and address the problem of the optimal definition of infringement penalties. We find both pro- and anti-innovation effects of overlapping patent portfolios, depending on the level of infringement penalties. We show that the possibility of hold-up can

¹The Patent Reform Act states that "the Court should conduct an analysis to ensure that a reasonable royalty [...] is applied only to that economic value properly attributable to the patent's specific contribution over the prior art."

actually facilitate the implementation of efficient R&D investments, provided that infringement fees are small enough and the firms' patent portfolios not too asymmetric.

The paper is structured as follows: We review the related literature in the next Section. We then introduce the model, our definition of social efficiency and the decentralized equilibrium in Sections 3 and 4. We study the case of symmetric firms in Section 5 before moving to the asymmetric case in Section 6. Section 7 concludes.

2 Related literature

Large overlapping patent portfolios are frequent in electronics and computer hardware and software, where they form "patent thickets" that firms have to navigate (Shapiro, 2001).² This situation results from a dramatic increase of firms' patenting propensity during the last two decades (Hall and Ziedonis, 2001; Shapiro, 2001; FTC, 2003; Graham and Mowery, 2003).³ It can be seen as the outcome of a prisoner's dilemma (Bessen, 2003), whereby firms reply to patent infringement threats by filing more patents, which they can use as counter threats. It generates transaction costs and double marginalization issues that reduce incentives to innovate.⁴ It also generates legal uncertainty that, as we

²More than "90,000 patents generally related to microprocessors are held by more than 10,000 parties", while "approximately 420,000 semiconductor and system patents [are] held by more than 40,000 parties" (FTC, 2003).

³The number of patents per million of U.S. dollars invested in R&D has doubled between 1982 and 1992 in the U.S. semiconductor industry (Hall and Ziedonis, 2001). Graham and Mowery (2003) find similar results for incumbent software firms during the 1990's.

⁴According to an industry executive, new semiconductor manufacturers must for instance pay \$100 million to \$200 million to license out-of-date manufacturing technologies (Hall and

show in this paper, can affect R&D competition in various ways.

When innovation is cumulative, it is well established that the risk of hold-up by an upstream patent owner can deter investments in downstream innovations (Scotchmer, 1991; Green and Scotchmer, 1995; Bessen, 2004). Green and Scotchmer (1995) show that this problem can be overcome if firms successfully negotiate a licensing agreement before R&D costs are sunk. However such ex ante contracts are actually quite rare (Anand and Khanna, 2000), because of information asymmetries with respect to existing patents (Reitzig et al., 2007), or on the cost and value of the future innovation (Bessen, 2004; Llobet, 2003).

We extend the analysis of patent hold-up to the case of competing firms that own their respective patent portfolios and that invest simultaneously in R&D. This approach can be related to an early paper by Fershtman and Kamien (1992), in which firms engage in parallel patent races for complementary innovations. Our model is, however, closer to Bessen (2003) and Bessen and Hunt (2007) in that it takes into account the possibility of patent litigation between former R&D competitors. Their papers consider as endogenous both patent filing and R&D decisions to establish the existence of a prisoner's dilemma between firms. By contrast, we consider exogenous patent portfolios, study their impact on market structure and R&D efficiency, and characterize optimal infringement penalties.

In the literature on patent litigation some papers focus on the definition of infringement penalties. Schankerman and Scotchmer (2001, 2005) and Anton and

Ziedonis, 2001).

Yao (2006) discuss whether applying the standard "lost profits" doctrine can deter infringement effectively when the patent protects a stand-alone innovation.⁵ However, this approach does not apply well to the case of multi-components technologies. Lemley and Shapiro (2006) focus on situations of hold-up when the patent covers one element of a broader technology. They defend the view that an injunction should not be applied to multi-component technologies when infringement was not voluntary, and emphasize the importance of infringement penalty definition. Our paper complements theirs by proposing a rule for defining optimal infringement penalties.

3 The model

We consider a model where two firms (firm 1 and firm 2) each undertake R&D investments to develop imperfectly substitutable products that will use the intellectual property that is embodied in its existing patents (and possibly in the existing patents of its rival as well). To keep matters simple we assume that firms have symmetric R&D functions: firm i ($i = 1, 2$) invests $\frac{\delta}{2}x_i^2$ to be successful with probability x_i where $\delta > 1$.

Each firm holds patents that it can assert against its competitor. With probability θ_i ($i = 1, 2$) firm j 's ($j \neq i$) product is judged to be infringing one of firm i 's patents by a court of law. The probabilities θ_1 and θ_2 are common knowledge so that each firm is able to anticipate perfectly the issue of litigation.

⁵The "lost profits" doctrine defines the infringement damage as the profits lost by the patent owner because the infringer imitated her invention.

We normalize the demand side by assuming that the monopoly profit is equal to 1 ($\pi^M = 1$) and the competitive profit (π^C) is given by

$$\pi^C = \frac{1 - \alpha}{2},$$

where $\alpha \in [0, 1]$ is a measure of product market's competitiveness given the characteristics of outputs 1 and 2.

The R&D and litigation stages can result in various market structures. Consider first that both firms have developed a product. The following states of nature may then arise:

- With probability $(1 - \theta_1)(1 - \theta_2)$ the court rejects both infringement claims. The firms become independent competitors on the product market, and each of them gets the competitive profit π^C .
- With probability $\theta_i(1 - \theta_j)$ the court upholds firm i 's infringement claim but rejects firm j 's. In this case firm i controls an essential technology input for firm j 's activity (at least from a legal viewpoint). It is thus entitled to evict its opponent from the market and enjoy a monopoly position. It gets the monopoly profit π^M while its opponent gets nothing.
- With probability $\theta_1\theta_2$ infringement is reciprocal. Then each firm controls a key technology input for its competitor's activity. A joint-profit maximizing solution consists of one firm's dropping out of the market and recovering half of the other firm's monopoly profit through a licensing

agreement.⁶

Assume firm i ($i = 1, 2$) successfully innovates, while its opponent fails and claims i 's new product infringes one of its patents.

- With probability $(1 - \theta_j)$ the court rejects the claim, and the innovator fully enjoys the monopoly profit π^M .
- With probability θ_j the court upholds the claim. Then the innovator has to pay an infringement penalty r_j to firm j .

The question we address is whether there exists a reasonable, non-negative infringement penalty r_i ($i = 1, 2$) that leads to efficient R&D investments. By reasonable we mean here that r_i must satisfy the ex-post voluntary participation and therefore technically require $r_i \leq 1$ for $i = 1, 2$.

To summarize the above, let π_i^k denote firm i 's expected revenue when firm k innovates. We have

$$\pi_i^i = 1 - \theta_j r_j \tag{1}$$

and

$$\pi_j^i = \theta_j r_j, \quad i, j = 1, 2 \text{ and } j \neq i. \tag{2}$$

When both firms innovate the expected profit to firm i (denoted π_i^{12}) is given

⁶Alternatively, one could imagine that firms successfully negotiate a cross-licensing agreement whereby each of them pays a per-unit royalty to its competitor on the product market. Depending on the level of royalty, such agreement could yield any profit level between competitive profits and monopoly profits. This alternative way of solving the double infringement case would not modify our results. For simplicity we thus keep as a working assumption the case in which firms share the monopoly profit.

by

$$\pi_i^{12} = \theta_i \left(1 - \frac{1}{2}\theta_j\right) + \pi^C (1 - \theta_i)(1 - \theta_j), \quad i, j = 1, 2 \text{ and } j \neq i. \quad (3)$$

4 Efficient investment and non-cooperative solution

We define efficient R&D investments as those that maximize the expected profits of a single joint venture company aggregating the R&D capacities of both firms. This definition is consistent with the standard result indicating that the hold-up problem can be solved ex ante if the patentee and the infringing innovator strike a licensing or joint venture agreement before the R&D costs are sunk (Green and Scotchmer (1995), Llobet (2003), Bessen (2004)). In our model a joint venture would make a monopoly profit if at least one product is developed. The corresponding expected profit is given by

$$JP = 1 - (1 - x)^2 - \delta x^2.$$

It is maximized by $x^* = 1/(1 + \delta)$. Having defined efficient R&D investments, we now turn to the equilibrium investments in the absence of an ex ante agreement. The expected profit to firm i when it invests is given by:

$$\Pi_i(x_i, x_j) = x_i(1 - x_j)\pi_i^i + x_j(1 - x_i)\pi_i^j + x_i x_j \pi_i^{12} - \frac{\delta}{2}(x_i)^2 \quad (4)$$

If it chooses not to invest, it can nonetheless extract some revenue using its portfolio. Its reservation payoff is then given by:

$$\Pi_i^R = x_j \pi_i^j = x_j (1 - \pi_j^j).$$

Firm i selects $x_i^*(x_j)$ such that

$$x_i^*(x_j) \in \arg \max_{x_i} \Pi_i(x_i, x_j),$$

and the firm chooses $x_i^*(x_j)$ if $\Pi_i(x_i^*(x_j), x_j) \geq \Pi_i^R$ and 0 otherwise.

5 Symmetric patent portfolios

As a first step we solve the model for an industry in which firms hold symmetric patent portfolios ($\theta_1 = \theta_2 = \theta$). Such symmetry can be viewed as featuring an industry in which incumbent firms have been accumulating patent portfolios at the same pace over time. Let π_M denote the profit of a firm that innovated while the other failed ($\pi_M = \pi_i^i$). Let π_D denote the profit of a firm if both firms innovated (with $\pi_D = \pi_i^{12} = \pi_j^{12}$). We have:

$$\pi_M = 1 - \theta r, \tag{5}$$

$$\pi_D = \theta \left(1 - \frac{1}{2}\theta\right) + \frac{1}{2}(1 - \alpha)(1 - \theta)^2. \tag{6}$$

Profit π_M is obviously decreasing in θ since hold-up deprives the single in-

novator from a part of her monopoly profit. By contrast it can be checked easily that π_D is increasing in θ , which is less intuitive. This is due to the effect of patent infringement on the market structure. Any successful infringement claim transforms a competitive product market into a monopoly. Hence stronger patents increase the expected payoff of the firms when both innovate.⁷

Lemma 1: *There exists a unique symmetric equilibrium in which both firms invest so as to achieve an innovation success probability x^S which is given by*

$$x^S = \frac{\pi_M}{1 + \delta - \pi_D}.$$

Proof: *See Appendix 1.*

Strikingly, the equilibrium innovation success probability x^S is increasing in π_M and π_D . Since θ decreases π_M but increases π_D , how changes in θ affect x^S is ambiguous. Overall we have

$$\text{sign of } \frac{dx^S}{d\theta} = \text{sign of } \alpha(1 - \theta)\pi_M - r(1 + \delta - \pi_D).$$

It follows directly that the effect of the litigation threat on R&D investments depends on the level of penalty r , and that R&D expenditure can be increasing in the litigation threat.

Lemma 2: Let $r_0 = 2\alpha/(1 + 2\delta + \alpha)$. For any $r \geq r_0$, then $\frac{dx^S}{d\theta} < 0$. For

⁷Note here that the positive effect of θ on π_2 still holds if we assume that the firms share less than the monopoly profit in case of double infringement.

any $r < r_0$, there is a unique $\theta_r \in [0, 1]$ such that $\frac{dx^S}{d\theta} \underset{<}{\geq} 0 \Leftrightarrow \theta \underset{>}{\leq} \theta_r$.

Proof: *See Appendix 2.*

Investments are decreasing in θ when $r \geq r_0$, and they are inverse U-shaped with respect to θ otherwise. A high infringement penalty r means that hold-up can deprive a single successful innovator from a large part of her monopoly profit. This negative effect dominates the market structure effect, and an increase in θ depresses investments. This case can be viewed as a free-riding pattern. Each firm has an incentive to let its competitor innovate and to sue it afterwards instead of developing its own innovation at the risk of being sued by its competitor.

If, by contrast, r is small, a successful innovator does not lose much if he is held up by an unsuccessful innovator. Hence the market structure effect dominates, and a higher θ actually reinforces the incentives to innovate. This finding implies that, for appropriate (low) levels of infringement penalty, the existence of a litigation threat can actually reinforce R&D investments in comparison with a situation where there is no legal uncertainty (e.g., where $\theta = 0$).

We now examine how these effects interplay with the efficiency of R&D. Note first that the optimal level of investment, which is based on an optimal innovation success probability $x^* = 1/(1 + \delta)$, is equal to the equilibrium investment if there is no litigation threat ($\theta = 0$) and firms make no profit if they compete in the product market ($\alpha = 1$). It follows that the additional profits due to imperfect competition on the product market ($\alpha < 1$) yield socially excessive R&D investments at equilibrium. In other words, firms start

an R&D race in the absence of a litigation threat.

Lemma 3: *On the assumption that $\theta = 0$, the equilibrium investment is such that the innovation success probability $x^S = x^*$ if $\alpha = 1$ and $x^S > x^*$ if $\alpha < 1$.*

Against this background of excessive investments, the existence of a litigation threat might work either as an accelerator or as a brake. If the infringement penalty is too weak, legal uncertainty actually reinforces the R&D race, contrary to what intuition suggests. By contrast, a relatively high infringement penalty might be sufficient to balance over-incentives to innovate by creating a free-riding pattern. Proposition 1 below states that this is possible under some conditions.

Proposition 1: *For any $\alpha \in [0, 1]$ there is unique $\theta(\alpha)$ where for any $\theta \geq \theta(\alpha)$ it is possible to implement first-best investments through an adequate transfer $r^* \in [0, 1]$.*

We have $\theta(0) = \frac{1}{2(1+\delta)}$, $\theta(1) = 0$ and $\frac{d\theta}{d\alpha} < 0$.⁸ The infringement penalty is such that (for any $\theta > 0$)

$$\theta r^* = x^* \pi_D \tag{7}$$

$$\Leftrightarrow r^* = \frac{\theta(2-\theta) + (1-\alpha)(1-\theta)^2}{2\theta(1+\delta)}. \tag{8}$$

Proof: Appendix 3.

⁸The expression for $\theta(\alpha)$ can be found in Appendix 3.

Figure 1 here

The figure above illustrates proposition 1. Equation (7) expresses the optimal balance between free-riding and a patent race. It requires that, conditional on the successful development of an innovation by its opponent, a firm's expected profit from a pure hold-up strategy equals its expected profit from investing efficiently in R&D. To guarantee $r^* < 1$, litigation threats must be sufficiently high. As θ becomes negligible, both the hold-up and the duopoly rents fall, and firms overinvest even if $r = 1$. This implies that a strong litigation threat might be not only useful, but also necessary to tame R&D races in sectors where product competition is mild.

Lemma 4: *The optimal infringement penalty r^* is non-increasing in α , δ , and θ .*

When the litigation threat is such that the first-best level of investment can be obtained, the infringement penalty must be calculated according to equation (8). Lemma 4 summarizes the properties of this efficient penalty. The infringement penalty should be low when competition in the product market is intensive and when R&D is costly, because in this case the R&D race is moderate. Lemma 4 also states that the optimal penalty should decrease as the litigation threat accentuates. This denotes the fact that at equilibrium the threat of litigation generates a free-riding pattern rather than additional incentives to innovate. In this context, and as indicated in equation (7), the probability of infringement

and the infringement penalty substitute for each other to maintain the optimal level of expected hold-up profit.

6 Asymmetric patent portfolios

Assume now that firms hold asymmetric patent portfolios ($\theta_1 \neq \theta_2$). Following our interpretation of patent portfolios as resulting from the firms' histories, we describe the asymmetric portfolio case as representing an incumbent (with the larger portfolio of patents) and a competitor that entered the industry more recently. Without loss of generality, let firm 1 refer to the firm holding a stronger portfolio ($\theta_1 > \theta_2$). Let r be the share of a single innovator's profit left to her opponent in the event of a successful infringement claim. Two outcomes can arise in equilibrium depending on whether the parameters θ_1 , θ_2 , δ and r satisfy the inequality given below:

$$\frac{\pi_2^2}{\pi_2^2 + \pi_2^1 - \pi_2^{12}} > \frac{\pi_1^1}{\delta}. \quad (9)$$

Lemma 5: *For each given values of the parameters θ_1 , θ_2 , δ and r the equilibrium is unique. It such that both firms invest in R&D if and only if (9) holds. Otherwise it is such that only firm 1 invests in R&D.*

Proof: See Appendix 4.

The inequality (9) does not hold when $\theta_1 r \rightarrow 1$ and δ is sufficiently high.

Two difficulties arise under asymmetric portfolios. First they induce asymmetric investment strategies even though the firms have identical R&D functions. Since efficiency requires that both firms invest the same amount, this is a factor of inefficiency. Moreover, strongly asymmetric portfolios can completely dissuade the firm with a weak portfolio from undertaking R&D. Then the portfolio works as a barrier to entry.

Proposition 2: *Provided discrimination is possible, setting r_1^* and r_2^* such that:*

$$\theta_i r_i^* = x^* \left\{ \pi_i^{12} + \frac{\delta}{\delta - 1} [\theta_j - \theta_i] \right\} \quad (10)$$

$$\Leftrightarrow r_i^* = \frac{\delta \pi_j^{12} - \pi_i^{12}}{\theta_i (\delta^2 - 1)}, \quad i, j = 1, 2 \quad i \neq j, \quad (11)$$

implements an efficient equilibrium.

The values r_1^ and r_2^* are such that $r_1^* < r_2^*$ and such that the firm with the weakest portfolio has greater expected monopoly rents.*

Proof: The efficient investment forms a pooling equilibrium if and only if it solves both best response functions:

$$\begin{cases} \delta x^* = (1 - \theta_2 r_2) - x^* [1 - \theta_2 r_2 + \theta_1 r_1 - \pi_1^{12}], \\ \delta x^* = (1 - \theta_1 r_1) - x^* [1 - \theta_1 r_1 + \theta_2 r_2 - \pi_2^{12}]. \end{cases}$$

Solving for r_1 and r_2 leads to (11). The proof of the second point is straightforward. ■

The infringement fees that restore R&D efficiency are comparable with the

optimal fee of Proposition 1. Although they are now different for each firm, they are similarly decreasing with the strength of the litigator's portfolio, the cost of R&D, and the intensity of market competition.

The expected rent of a patent holder depends once again on the duopoly profits that each firm would make, except that it is now corrected by the difference in the strength of the two firms' property rights. As in the symmetric case, the optimal penalty should decrease as the litigation threat accentuates. This implies that the firm with the stronger portfolio gets less than its expected duopoly profits conditional on investing efficiently while the firm with the weakest portfolio gets more. The amount added or deducted from the duopoly rents is proportional and inversely correlated to the cost of R&D (δ).

Since we must have $r_i^* \in [0, 1]$, the parameters (θ_1, θ_2) for which r_1^* and r_2^* are well defined are such that $\theta_i \in [L(\theta_j), U(\theta_j)]$ with

$$U(\theta_j) = \frac{2\delta\theta_j + (\delta - 1)(1 - \alpha)(1 - \theta_j)}{1 + \delta - \alpha(\delta - 1)(1 - \theta_j)}$$

and

$$L(\theta_j) = \frac{2\delta\theta_j + (\delta - 1)(1 - \alpha)(1 - \theta_j)}{2\delta^2 + \delta - 1 - \alpha(\delta - 1)(1 - \theta_j)}$$

for $i = 1, 2$ and $j \neq i$. It is obvious that these boundaries define a non-empty interval. Appendix 5 analyzes the functions $U(\theta)$ and $L(\theta)$ in greater detail. Figure 2 (below) gives a visual representation of the interval where θ_1 and θ_2

must lie for an efficient equilibrium to exist.

Figure 2 here

It clearly shows that even with discriminatory fees, efficiency cannot be reached when the patent portfolios are strongly asymmetric. Put differently, the efficiency result obtained for symmetric portfolios is robust only to the introduction of limited asymmetries, on the condition that fees can be tailored as a function of each firm's portfolio.

7 Conclusion

The threat of patent hold-up is generally deemed as an impediment to innovation in some industries. In this paper we investigate whether it can be used to balance socially excessive investments when two firms compete in R&D under the reciprocal threat of patent litigation. We consider a situation where the market structure is determined successively by the probabilistic outcomes of R&D and patent litigation. In this context we characterize infringement fees that allow efficient R&D investments in the overall R&D game.

Depending on the level of infringement fees, we find that the reciprocal threat of patent hold-up can either reinforce incentives to innovate or reduce total R&D investments. The first effect is due to the positive impact of patent litigation on industry concentration. It dominates when infringement fees are low. As infringement fees increase, it is outweighed by the risk that an innovator will

be deprived of part of its profits by an opportunistic patent holder. In this case the reciprocal threat of hold-up creates a free-riding pattern whereby each firm prefers to let its competitor develop an innovation and then sue it.

We show that optimal R&D investment can be implemented by tuning the infringement fees so that the free-riding effect dominates. This solution can be implemented under some conditions, namely when infringement is sufficiently likely and when portfolios are close to symmetric.

High infringement probabilities facilitate the implementation of efficient R&D investments because they increase the investments' sensitivity to the infringement fee. Since both infringement likelihood and infringement fees then reduce incentives to innovate, maintaining the correct level of incentives requires that infringement fees be decreasing in the strength of the infringed patent portfolio. When patent portfolios are symmetric across the industry, this implies that infringement royalties should be lower when the patent portfolios overlap to a greater extent. We find that this result can be extended to weakly asymmetric portfolios on the condition that the fees can be differentiated. However, when the patent portfolios are strongly asymmetric, there is no reasonable fee that can implement efficiency. The firm with the stronger portfolio therefore invests excessively and deters its competitor.

Appendix

Appendix 1: Proof of Lemma 1

The reaction functions are given by

$$x_i(x_j) = \max \left\{ \frac{\pi_M - x_j(1 - \pi_D)}{\delta}, 0 \right\}, \quad (12)$$

$i = 1, 2$ and $j \neq i$.

The reaction functions are downward sloping since $(1 - \pi_D) > 0$. Moreover, since $\frac{\pi_M}{\delta} < \frac{\pi_M}{1 - \pi_D}$ no asymmetric equilibrium in which a firm invests $\frac{\pi_M}{\delta}$ while the other invests 0 is possible. The best reply functions cross once and the symmetric equilibrium described in the proposition is unique. In addition, plugging back the best reply into firm i 's profit leads to

$$\max_{x_i} \Pi^i = \Pi_R^i + \frac{\delta}{2} [x_i(x_j)]^2 > \Pi_R^i.$$

Thus the participation constraints holds strictly. ■

Appendix 2: Proof of Lemma 2

Claim: Given any $\theta \in [0, 1]$, there exists a unique r_θ such that $\frac{dx^s}{d\theta} > 0 \Leftrightarrow r < r_\theta$. We have $\frac{dr_\theta}{d\theta} < 0$.

Proof: The sign of $\frac{dx^s}{d\theta}$ is given by the following function:

$$F(r, \theta) = \alpha(1 - \theta)\pi_M - r(1 + \delta - \pi_D).$$

We have

$$F(0, \theta) = \alpha(1 - \theta) \geq 0$$

and

$$F(1, \theta) = \alpha(1 - \theta)^2 - (1 + \delta) + \pi_D < 0,$$

since $\pi_D < \frac{1}{2}$ and $(1 + \delta) \geq 2$. The function $F(\cdot)$ is continuous in r . Thus for each θ there exists at least one r_θ such that $F(r_\theta, \theta) = 0$. Finally since

$$\frac{\partial F}{\partial r} = \pi_D - \theta(1 - \theta)\alpha - (1 + \delta) < 0,$$

r_θ is unique. Since $\frac{\partial F}{\partial \theta} = -\alpha\pi_M < 0$ we have $\frac{dr_\theta}{d\theta} = -\frac{\frac{\partial F}{\partial \theta}}{\frac{\partial F}{\partial r}} \Big|_{r=r_\theta} < 0$. Thus $r(\theta) < r(0) \equiv r_0$. ■

Consequently, the above one-to-one relationship implies that for any given $r < r_0$ there exists a unique θ_r such that $\frac{dx^s}{d\theta} > 0 \Leftrightarrow \theta < \theta_r$.

Appendix 3: Proof of Proposition 1.

It is possible to implement the socially efficient investment associated with the innovation success probability $x^S = x^*$ if and only if there exists a unique $r^* \in [0, 1]$ that satisfies

$$\theta(1 + \delta)r^* = \theta \left(1 - \frac{\theta}{2}\right) + \frac{(1 - \alpha)}{2}(1 - \theta)^2. \quad (13)$$

We have an equality of the form $Ar^* = B$ where A and B are non-negative. Hence r^* is non-negative. All that remains is to identify the set of parameters

(θ, α) such that $r^* \leq 1$. Consider the following function

$$F(\theta, \alpha) = \theta \left(1 - \frac{\theta}{2}\right) + (1 - \theta)^2 \frac{(1 - \alpha)}{2} - \theta(1 + \delta).$$

There exists a unique $r^* \leq 1$, implementing socially efficient investments, if and only if the parameters θ and α are such that $F(\theta, \alpha) \leq 0$. We have

$$F(0, \alpha) \geq 0$$

and

$$F(1, \alpha) < 0.$$

Since $\frac{\partial F}{\partial \theta} < 0$, there exists a unique $\theta(\alpha)$ such that $F(\theta(\alpha), \alpha) \equiv 0$ and such that $F(\theta, \alpha) \leq 0$ for all $\theta \geq \theta(\alpha)$.

Specifically we have

$$\theta(\alpha) = \frac{\sqrt{(\delta + 1 - \alpha)^2 + \alpha(1 - \alpha)} - (\delta + 1 - \alpha)}{\alpha} \forall \alpha > 0$$

and $\theta(0) = \frac{1}{2(\delta+1)}$. Finally, since $\frac{\partial F}{\partial \alpha} < 0$, we have $\frac{d\theta}{d\alpha} < 0$.

Appendix 4: Proof of Lemma 5

In the asymmetric case, the reaction curves are given by

$$\delta x_1 = \pi_1^1 - x_2 S_1(\theta_1, \theta_2) \tag{14}$$

and

$$\delta x_2 = \pi_2^2 - x_1 S_2(\theta_2, \theta_1) \quad (15)$$

where

$$S_i(\theta_i, \theta_j) = \pi_i^i + \pi_i^j - \pi_i^{12}.$$

and where π_i^j and π_i^{12} $i, j = 1, 2$ are defined by (1), (2), and (3). To establish the results stated in Lemma 5 we proceed as follows: First we show that the reaction functions are downward sloping. Second, we show that if there is an interior solution, it is unique. We fully characterize it. Last we show that there exists configurations of parameters such that $x_2 = 0$ in equilibrium.

- The reaction functions are downward sloping.

It is straightforward to verify that $S_1(\theta_1, \theta_2) \geq 0$ so that the first reaction function is downward sloping. For any given θ_j ($j = 1, 2$) $S_2(., .)$ is linear in θ_i . Let $a = \frac{1}{2}(1 - \alpha(1 - \theta_2))$ and $b = \frac{1}{2}(1 + \alpha(1 - \theta_1))$. For $r \in [0, a]$, we have $\frac{\partial S_2}{\partial \theta_2} < 0$, $\frac{\partial S_2}{\partial \theta_1} > 0$ and thus

$$S_2(\theta_2, \theta_1) > S_2(\theta_2, \theta_2) > 0.$$

For $r \in [a, b]$, we have $\frac{\partial S_2}{\partial \theta_2} < 0$, $\frac{\partial S_2}{\partial \theta_1} < 0$ and therefore $S_2(\theta_2, \theta_1) > S_2(1, 1) > 0$. Finally for $r \in [b, 1]$, we have $\frac{\partial S_2}{\partial \theta_2} > 0$, $\frac{\partial S_2}{\partial \theta_1} < 0$ and thus $S_2(\theta_2, \theta_1) > S_2(0, 1) > 0$. Thus we always have $S_2(\theta_2, \theta_1) > 0$ so that the second reaction function is also downward sloping.

- If interior, the solution is unique.

Consider a situation where we have

$$\frac{\pi_1^1}{\pi_1^1 + \pi_1^2 - \pi_1^{12}} > \frac{\pi_2^2}{\delta} \text{ and } \frac{\pi_2^2}{\pi_2^2 + \pi_2^1 - \pi_2^{12}} > \frac{\pi_1^1}{\delta}.$$

In that case, there is at least one interior equilibrium. In equilibrium (15) and (14) hold so that

$$x_2 = \frac{\pi_1^1}{S_1(\theta_1, \theta_2)} - x_1 \frac{S_2(\theta_2, \theta_1)}{\delta}.$$

and

$$x_2 = \frac{\pi_2^2}{\delta} - x_1 \frac{S_2(\theta_2, \theta_1)}{\delta}.$$

Firm 1's reaction function is steeper than firm 2's (when setting x_2 on the vertical axis) since

$$\delta^2 > S_1(\theta_1, \theta_2) S_2(\theta_2, \theta_1).^9$$

Therefore, any equilibrium where $x_1 > 0$ and $x_2 > 0$ is unique. Let x_i^{AS} denote firm i 's innovation success probability, we have

$$x_i^{AS} = \frac{\delta \pi_i^i - \pi_j^j [\pi_i^i + \pi_j^j - \pi_i^{12}]}{\delta^2 - [\pi_i^i + \pi_j^j - \pi_i^{12}] [\pi_j^j + \pi_j^i - \pi_j^{12}]}, \quad i, j = 1, 2, i \neq j,$$

where π_i^j and π_i^{12} $i, j = 1, 2$ are defined by (1), (2), and (3). Plugging back the reaction function into a firm's profit leads to

$$\max_{x_i} \Pi^i = \Pi_R^i + \frac{\delta}{2} [x_i(x_j)]^2 > \Pi_R^i \text{ for } i = 1, 2.$$

⁹Indeed, we have $S_1(\theta_1, \theta_2) S_2(\theta_2, \theta_1) < 1 - (\theta_1 r_1 - \theta_2 r_2)^2 < 1$ and $\delta > 1$.

Thus the participation constraint is satisfied.

- For some values of the exogenous parameters, the equilibrium is such that $x_2 = 0$. However we always have $x_1 > 0$.

Since

$$\frac{\pi_1^1}{\pi_1^1 + \pi_1^2 - \pi_1^{12}} > \frac{\pi_2^2}{\delta}$$

there is no equilibrium with $x_1 = 0$.

To guarantee that the reaction curves cross at a point where $x_2 > 0$ we must have

$$\frac{\pi_2^2}{\pi_2^2 + \pi_2^1 - \pi_2^{12}} > \frac{\pi_1^1}{\delta}.$$

Depending on the values of θ_1 , θ_2 , δ and r the above inequality may or may not hold. For instance let $\theta_1 = 1$, $\theta_2 = 0.5$, $r = 0.98$ and $\alpha = 1$. For any $\delta > 6.7$ we have $x_2 > 0$ in equilibrium and for any $\delta \leq 6.7$ we have $x_2 = 0$ in equilibrium. ■

Appendix 5: Analysis of the functions $U(\theta)$ and $L(\theta)$.

It is obvious to show that $U(\theta) > L(\theta)$. We have

$$\text{sign of } \frac{dU}{d\theta} = 2\delta + (1 - \alpha) + \delta^2(1 + \alpha) > 0.$$

Then $U(0) > 0$ and

$$U(\theta) > \theta \Leftrightarrow (\delta - 1) \left[1 - \alpha(1 - \theta)^2 \right] > 0.$$

We have

$$\text{sign of } \frac{dL}{d\theta} = \delta^2 (4\delta - (1 - \alpha)(2\delta + 1)) + (1 - \alpha)(4\delta^2 - 1) > 0.$$

Then $L(0) > 0$ and there exists a unique θ' such that $L(\theta') = \theta'$. The former result can be established considering that $L(\theta) = \theta$ if and only if

$$2\delta\theta + \theta - (1 - \alpha) - \alpha\theta(1 - \theta) = 0.$$

The left-hand side is an increasing function so that only one θ' solves the equality. Figure 2, in the text, summarizes the above findings.

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