Strategic Collaboration in Dynamic R&D Competitions

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Abstract

I develop a model to study the strategic decision to collaborate in a multi-stage R&D race by a technological leader and a follower. I examine how individual decisions are affected by the strength and the breadth of the Intellectual Property (IP) regime in place, where the breadth defines the stages in which the innovator is granted IP rights, and the strength is a measure of the bargaining power over the value generated by the new technology. I show that, under a narrow patent protection, a weak system may fail to produce collaboration among innovators because it creates an incentive for the followers to strategically postpone imitation to better free-ride on the efforts of the leaders. So the optimal strength of protection is never ”minimal” and it is increasing in the costliness of R&D efforts, as more complicated innovations induce firms to collaborate to share the risk of failure. However, with finite costs, the optimal strength is never “maximal”—as in a winner-takes-all competition,—because the presence of spillovers can encourage more R&D effort by firms. Finally, I find that a broad protection, while it may encourage disclosure, can postpone imitation to a great extent, and reduce the overall R&D effort exerted by firms.

JEL classification: L5; L2; D9.

1 Introduction

The traditional economic rationale for Intellectual Property (IP) protection is that imitation can inhibit R&D investments (Arrow, 1962). However, if innovation is modeled as a patent race with technological spillovers, a profit maximizing firm may want to encourage imitation from rivals because it can reduce the overall R&D cost to achieve the objective of the race (De Fraja, 1993). In a similar way, when innovation is cumulative, firms in the early stages of the innovation process may choose to reveal their findings to the owners of certain complementary assets, even if they are competitors, in order to accelerate the development of the next stages (Bessen and Maskin, 2009; Fershtman and Markovich, 2010). These insights offer a compelling theoretical reason to prefer weak regimes of IP protection as a means to further the voluntary collaboration among innovators.

In this article I reconsider some of these theoretical insights, to show how they may have induced researchers to estimate the potential benefits from a weak system to be larger than they really are. I begin by noticing that, in a setting in which innovation is cumulative, the disclosure aspect of placing basic knowledge in the public domain does not necessarily serve the purpose of enabling the rivals to conduct research in the development of new commercial applications (Harhoff et al., 2003; Hall and Harhoff, 2012). Incentives are needed for dealing with the costs of imitation which may limit the diffusion of new findings (Mansfield et al., 1981), but also to induce firms to invest in R&D without any strategic free-riding. Thus, the role of the legal environment is twofold. On the one hand, the IP system should be designed to encourage a timely disclosure of basic knowledge (Scotchmer and Green, 1990; Scotchmer, 1991). On the other hand, it should also set the right incentives for firms to promptly imitate and to put in use the findings that reside in the public domain.

Here, I argue that pursuing these two goals at the same time is often out of reach, because while the social planner may want to lower the strength of patent protection in order to raise the incentives for a timely disclosure of basic research (Bessen and Maskin, 2009), by lowering it, it may also provide an incentive for rivals to postpone imitation, because, by doing so, they will encourage greater R&D efforts from the first-generation innovators. Thus, I examine a setting in which the decision to adopt and copy the open knowledge is not modeled as a fixed externality (d'Aspremont and Jacquemin, 1988) or a direct consequence of disclosure (Green and Scotchmer, 1995), but it is the outcome of a strategic interaction between firms. Formally, I develop a game theoretic model of two-stage innovation, in which a second innovation builds upon the first (Grossman and Shapiro, 1987; Scotchmer and Green, 1990; Scotchmer, 1991; Green and Scotchmer, 1995; O'donoghue et al., 1998; Denicolò, 2000), and where the first agent to progress by one stage can decide whether to disclose the details of its innovation, or to keep them secret, and then the follower makes a decision on whether to imitate the available knowledge, or wait. In this setting, collaboration occurs only if it is incentive compatible in the sense that the one who possess the superior knowledge will also intend to make the knowledge public, and the one who is expected to acquire and improve upon the new knowledge, finds profitable to do so. It turns out that a weak regime of IP protection may fail to promote an incentive-compatible collaboration among rivals, because, while it succeeds in persuading the leader to disclose the new findings, it also makes optimal for the follower to postpone imitation until the leader has achieved all stages of research, and only then imitate the public knowledge to grab a share of the lucrative commercialized new technology.

A case in point is perhaps the controversial role of the so called "me-too" drugs in the pharmaceutical industry (Angell and House, 2005). "Me-too" drugs are merely variations of already developed drugs, and are a kind of follow-on innovations that are not considered a genuine and valuable innovation. This is made possible by the fact that the FDA usually approves a drug only if it is better than a placebo, and there is no way of knowing if the new drug improves a particular treatment already on the market (Angell and House, 2005). Although controversial (DiMasi and Faden, 2010), pharmaceutical companies have been accused to have been taking away resources from more fundamental research, to invest efforts and money in the commercialization of these poorly innovative drugs. According to my model, it is at least conceivable that the lack of legal barriers in the downstream market is one of the main causes of this distortion.

To see this point, consider the following simple example of two firms competing in a two-stage patent race. Suppose that the first stage consists of improving basic research that cannot be commercialized as it is, but that is necessary to develop a new drug with potential for reaching a large downstream market. Suppose that the IP system is weak and the second stage can always be reverse-engineered at no cost.[1] Lacking any legal or technical protection, if one firm achieves the first stage, it may fit in well with its needs to make the new knowledge freely available so as to enable the rival to share the costs of R&D for the next stage. Suppose

[1] Otherwise, the presence of a lead-time or the costliness of the process of reverse engineering would serve the same function as a short-lived intellectual property right (Samuelson and Scotchmer, 2001).

further that the technology is sufficiently complex or "sticky" (as in Von Hippel, 1994) that, to enable the rival to put in use the new technology, the innovator may have to provide the other firm with the access to a common asset (e.g., a research tool) or some form of direct collaboration between agents (e.g., organize a few meetings, plan some visits). So that we can actually model imitation as a bilateral decision of collaboration. At this point, the rival will anticipate that the lack of IP rights will offer an opportunity to wait until also the second stage has been achieved, and delay imitation until the new technology has been commercialized. In other words, if technology is sufficiently complex, the rival can always make a choice between collaborating to acquire and improve upon the new technology (e.g., access the common asset), or ignoring it to better free-ride on the effort of the rival. As a result, in equilibrium, there is less R&D effort in the development of breakthroughs, while more firms will be engaged in the imitation of the commercialized new technologies, if that occurs.[2]

In this article I use the developed model to examine the consequence of collaboration on the design of an optimal IP system. I first focus on the optimal strength of the system, and I show not only that the optimal strength is strictly positive, but it is also increasing in the costliness of the R&D effort. I further show that the optimal strength is never maximal in the sense that it is never optimal to design an IP system based on a winner-takes-all principle. I also consider the opportunity to make patent protection broad, so I examine the effects arising in equilibrium from extending the legal protection obtained in one stage to the next stage (Gilbert and Shapiro, 1990; O'donoghue et al., 1998; Denicolò, 2000).

[2] Which in turn will make competition in the downstream market tougher, and therefore the development of breakthroughs even less rewarding

It turns out that a narrow protection is more desirable from an ex-ante perspective, because broad protection lowers too much the incentives for firms to collaborate during the race. Overall, the model is very simple, but its simplicity highlights the important role of strategic decisions in collaboration made by firms during a dynamic R&D competition, which I believe is an important step towards a better understanding of how the IP can stimulate technical progress and economic growth.

The rest of the article is organized as follows. In the next section, Section 2, I introduce the baseline model. In Section 3 I characterize the equilibrium actions of firms. Then, I discuss the design of an optimal IP system in Section 4, in which the Subsection 4.1 deals with the problem of setting the optimal strength, and Subsection 4.2 analyzes the effects of the breadth on the incentives to collaborate. Finally, Section 5 summarizes the main results and concludes.

2 The Model

I consider a two-period two-stage patent race with two firms in which each firm i makes an R&D effort of intensity $x_i \in [0,1]$ at every period. For simplicity, I postulate a linear relation $\phi : [0,1] \to [0,1]$ between the R&D intensity and the probability of improving by one stage in the race, which is the identity function.[3] At each period, the two firms choose their efforts simultaneously. An effort x_i

[3] One possible 'micro-foundation' for this assumption is that innovating means to improve the state of the art by a given factor Q. Achieving any lower level, $q < Q$, means failing to innovate. If effort x generates an improvement of $q = x + \eta$, where η is randomly drawn by a uniform distribution F, then the probability of innovating is $\phi(x) = 1 - F(q - x)$ which is strictly increasing and linear in x.

causes a disutility or cost denoted $c(x_i)$, where $c : [0, 1] \rightarrow R_+$ is a quadratic function with $c(0) = 0$ to reflect the existence of diminishing returns to R&D efforts.

Achieving the first stage yields a payoff normalized to zero—as from basic research that can not be commercialized as it is.[4] Achieving the second stage yields an aggregate payoff of $2\pi > 0$—as from the commercialization of two applications. The division of profits between firms is determined by the *breadth* and the *strength* of the IP system in place (as in Green and Scotchmer, 1995; Denicolò, 2000). In the baseline model, I consider a situation in which the breadth of the patent for each stage is *narrow*, and therefore its legal protection does not extend to the next stage. Since the first stage yields no payoffs, I assume without loss of generality that only the second stage is patentable. Thus, the first firm to develop all stages will enjoy exclusive IP rights on the innovation (i.e., the other firm will have to pay out royalties in order to lawfully exploit any application based on the second stage technology).[5] Later I will discuss what happens when the patent system is no longer *narrow*, and the legal protection—eventually obtained for the first stage—extends to the next stage.

The importance of being granted patent protection is then determined by the *strength* of the IP system. This is modeled as a profit-sharing rule denoted by $\alpha \in (0, 1)$ according to which, if the second stage innovation has been achieved, the firm who holds the IP rights—i.e., the first to achieve the second stage—

[4] Notice, this is only for simplicity. The presence of a positive payoff after one period, while it will surely raise the overall levels of R&D effort, it will not affect the incentives to share knowledge at that period, and therefore it does not alter the results.

[5] Since time is discrete, I further assume that when two firms achieve the second stage in the same period, the patent is randomly assigned.

obtains a payoff of $(1+\alpha)\pi$, whereas the other firm obtains a residual payoff of $(1-\alpha)\pi$. In other words, I assume that the scope of the patent determines the stage at which the innovator can be granted IP rights over the payoffs produced by the final innovation, and the strength of the IP system determines the bargaining power of the patent holder over the overall value generated by the new technology. This setting encompasses and generalizes a number of different situations. For instance, the individual payoffs can result from ex-post licensing when imitation leads to different applications as in the model of Gallini and Winter (1985), or even from settlement agreements to avoid litigation as in the model of Meurer (1989).

The innovation process is sequential and collaboration is a strategic decision made by each firm. Let $s_i \in \{0,1,2\}$ denote the number of stages achieved by each firm i, with $s_i = 0$ when the race starts, since firms have not achieved any stage at the beginning of the race. After each period, the R&D efforts produce a vector $\mathrm{s} = (s_i, s_j)$ which is observed by every firm, before they make their effort decisions.[6] At this point, if $\mathrm{s} \in \{(0,1),(1,0)\}$, there is an interim stage in which the firm who has achieved the first stage—the technological leader—can choose to make its knowledge available in the public domain, or to keep it secret.[7] Then, the

[6] The assumption of “awareness” of the results obtained by the rival is in general a strong assumption to make. Nevertheless, if firms are not aware of what the rivals are doing, collaboration will never occur. So to some extent, we should expect some form of awareness in markets where collaboration is expected to be of value to progress in research.

[7] Here I am assuming that trade secrecy is perfect at the intermediate stage, so that there are no risks of any involuntary leaks associated with it. However, the model can be extended in order to incorporate the possibility of involuntary leaks of information as an exogenous probability $\iota > 0$ that the other firm will learn the technology kept secret. Results do not change if the ι is sufficiently small.

other firm—the follower—makes a choice on whether to imitate the knowledge, or wait until the second stage has been eventually commercialized. This phase can potentially yield a new vector s' in which the number of stages achieved by the firm lagged behind in the race is increased by one (at no costs).[8] Notice that I am implicitly assuming that the technological knowledge is sufficiently *complex*, and that firms have to collaborate (e.g., access to a common research tool) in order to enable the follower to progress in the race. Sometimes, however, it will be useful to consider the alternative case in which the technological knowledge is, say, *simple* and the decision of disclosure by one firm yields a perfect knowledge sharing.

In summary, the timing of the game is as follows: firms simultaneously make a R&D effort, their progresses are revealed at the beginning of the next period, then they decide whether to share knowledge or not, and they again make R&D efforts simultaneously. Finally payoffs are realized.

3 Equilibrium R&D Efforts

In this section I focus on the pure-strategy subgame-perfect equilibrium of the game. I proceed by backwards induction and I compute the Cournot-Nash levels of R&D intensity for each subgame.

Let $l \in \{0, 1, 2\}$ denote the periods left to play. Since there are two firms, innovation is sequential and it involves binary outcomes, there are at most 2^2

[8] If imitation was delayed or with high costs, the presence of a lead-time or the costliness of the process of reverse engineering would serve the same function as a short-lived intellectual property right (Samuelson and Scotchmer, 2001). By assuming a costless imitation, I am focusing on an extreme scenario where IP rights are most needed.

possible outcomes to consider at any subgame. So I can write the expected payoff for each firm i when there are $l+1$ periods left to play as it follows:

$$
\begin{aligned}
V_i(\mathbf{s}|l+1) =& x_i[x_j V_i(s_i+1, s_j+1|l) + (1-x_j)V_i(s_i+1, s_j|l)]+ \\
&+ (1-x_i)[x_j V_i(s_i, s_j+1|l) + (1-x_j)V_i(s_i, s_j|l)] - c(x_i)
\end{aligned} \tag{1}
$$

Since expression (6) is concave in x_i, the first order conditions are also sufficient for an optimum. By assuming that firms are rational and maximize their expected profits, they will play the Cournot-Nash equilibrium at each subgame. The Cournot-Nash expected payoffs are then denoted by $V^*(\mathbf{s}|l+1)$, where I can drop the index i because firms are symmetric given $\mathbf{s}$. Then, a necessary and sufficient condition for collaborating and sharing the knowledge at the interim stage can be written as it follows:

$$
V^*(\mathbf{s}=(1,1)|1) \geq \max\{V^*(\mathbf{s}=(1,0)|1), V^*(\mathbf{s}=(0,1)|1)\} \ , \tag{2}
$$

which simply means that the expected payoffs from collaborating are greater or equal than the max between the expected payoffs from being a leader, and those from being a follower.

If I assume $c > \pi$ to guarantee an interior solution, the next proposition yields the following:

Proposition 1. *Under narrow patent protection, when* $\mathbf{s} \in \{(1,0),(0,1)\}$ *and there is one period left to play, firms will share their knowledge at the interim stage if and only if*

$$
\frac{8c^2 - \pi^2}{8c^2 + 8c\pi + \pi^2} \geq \alpha \geq \frac{-2c^2 + 2c\pi + \pi^2}{2c^2 + 2c\pi + \pi^2} \tag{3}
$$

Proof. See Appendix A. □

This first result ties together the degree of enforcement of the IP system with the occurrence of knowledge sharing or collaboration in research. It also formally shows why collaboration may not necessarily occur by an act of disclosure alone. When there is one period left to play, the upper limit of inequality (3) needs to be satisfied and α needs to be sufficiently low to ensure that the leader will make her intermediate technology freely available to the follower. Otherwise the leader will rather prefer to keep the new findings secret, because the marginal benefit from increasing the probability of developing the next stage by encouraging greater R&D from the rival is offset by the diminished probability of being granted patent protection, which is obviously increasing in its value when α is larger. The lower limit of inequality (3), by contrast, ensures that the follower will not decide to free-ride on the leader's R&D activity by ignoring the available knowledge, waiting to imitate all at once the commercial application brought to the market by the leader in the next period. Again, this decision trades off with the risk of a failure of the innovation process. So, when α is sufficiently small, the marginal benefit of "free-riding" is offset by the lower probability of developing the innovation in the next period.

[**FIGURE 1 HERE**]

Figure 1 illustrates the main comparative static properties of this result. The darker region in the middle of the plot indicates where inequality (3) is satisfied, and collaboration occurs in equilibrium. The upper region of the plot indicates where collaboration fails, because the leader decides to keep the intermediate knowledge secret. The bottom region of the plot indicates where collaboration does not occur either, because, while the leader disclose her technology, the follower prefers to free-ride. Overall, the interval of values of α in which collaboration occurs in equilibrium expands as the marginal cost of R&D c increases. That is, as c goes up, the *minimum* level of enforcement necessary to induce the leader to disclose her findings increases, whereas the *maximum* level of enforcement necessary to prevent free-riding reduces, eventually becoming null.

I can now report the subgame perfect equilibrium in the next proposition.

Proposition 2. *Under narrow patent protection, the subgame perfect equilibrium R&D intensity of firms is the following. Firms will collaborate at the interim stage as in proposition 1. Then, when there are $l = 1$ periods left to play,*

$$x^*(1) = \begin{cases} \frac{\pi(1+\alpha)}{2c+\pi} & \textit{if } \mathbf{s} = (1,1) \\ \frac{\pi(1+\alpha)}{2c} & \textit{if } \mathbf{s} = (1,0) \\ 0 & \textit{if } \mathbf{s} \in \{(0,0),(0,1)\} \end{cases}$$

When there are $l = 2$ periods left to play,

$$x^*(2) = \begin{cases} \frac{V^*(\mathbf{s}=(1,1)|1)}{2c+V^*(\mathbf{s}=(1,1)|1)} & \textit{if (3) is satisfied} \\ \frac{V^*(\mathbf{s}=(1,0)|1)}{2c+V^*(\mathbf{s}=(1,1)|1)-V^*(\mathbf{s}=(1,0)|1)+V^*(\mathbf{s}=(0,1)|1)} & \textit{otherwise.} \end{cases}$$

Proof. See Appendix A. □

In equilibrium, when there is one single firm exerting a positive effort in R&D, the individual effort of this firm is always higher than what the firm would do if the rival was also investing in R&D. However, it is also easy to show that the aggregate R&D effort when all firms participate in research is always higher than the level exerted in equilibrium by one single firm. These results simply reflect the presence of diminishing returns to R&D effort, and imply that the probability of achieving the second stage is always larger when both firms are investing in R&D (as assumed in Bessen and Maskin, 2009).

Moving back to the first period, it is also interesting to note that individual efforts are always higher if firms expect to collaborate at the next period (indeed one can rewrite the expression reported in the proposition as the max between the two levels). This seems to suggest that firms my prefer lowering α to benefit from an increased probability of achieving the second stage innovation, as well as the opportunity of reducing individual effort. In the next section we fully explore this hypothesis.

4 The Design of an Optimal IP System

4.1 Optimal Strength

Let's assume, for simplicity, that firms incorporate the entire social value of the innovation, i.e., $W = 2\pi$, so that outcomes are always ex-post efficient, if firms achieve the second stage.[9] This also implies that there are no losses associated with the anti-competitive nature of patent protection (which is an other important topic but well understood in the existing economic literature, e.g., Chang, 1995), and therefore the only reason to weaken the patent protection regime is that it can potentially raise the incentives for firms to share their knowledge during the

[9] Although this may not be a realistic representation of any specific market, a similar setting can occur—in theory—in markets where the demand is inelastic, or in which firms are selling products sufficiently differentiated. For example, pharmaceutical companies using the same compound or technology to treat different diseases or medical conditions.

race.[10]

The problem of maximizing the social welfare is then the same problem of choosing a value of $\alpha \in (0,1)$ that maximizes the sum of the expected payoffs for firms at the beginning of ther race, i.e., when $l = 2$. Thus, I imagine the social planner as an agent that moves first and, anticipating the equilibrium of the game between firms, selects an optimal level of α as it follows:

$$\max_{\alpha \in (0,1)} W^e = \sum_i V_i(\mathbf{s} = 0, 0 | l = 2) = 2V^*(\mathbf{s} = 0, 0 | l = 2) \ . \tag{4}$$

where W^e denotes the expected social welfare.

Because of proposition 1, it is clear that the objective function (4) can have one or more discontinuities in α as the regime changes from encouraging to stifling collaboration at the interim stage. This can be seen in Figure 2. In equilibrium, the relationship between W^e and α is a piecewise continuous and non-monotonic function, which is shown by the solid black curve on the figure. This is the result of two patterns described by the red and the blue dashed curves. The red dashed curve shows the relationship between W^e and α that would occur if firms were always collaborating at the interim stage (i.e., a situation in which the leader would always disclose its findings and the follower would always want to acquire the available knowledge). I let W^e_c denote this "cooperative" situation. The blue dashed curve depicts instead the relationship that would occur if firms were never

[10] One way to modify this assumption is to consider a more realistic downstream market parametrized by a variable $\delta \in [0,1]$ that captures all the possible underlying competition settings, ranging from Bertrand competition ($\delta = 0$) to collusion ($\delta = 1/2$). In this modified scenario, the private value of the innovation can be lower than the social value, because part of it goes to consumers in the form of consumer's surplus. Results would not change substantially under this setting.

collaborating at the interim stage, which I denote by W^e_{nc}.

[**FIGURE 2 HERE**]

It is interesting to note that both dashed curves of Figure 2 are bell-shaped, and this feature holds more generally (for all levels of c and π). This implies that each curve admits a unique optimum level of α, which is also interior to the interval $(0, 1)$. This result can be surprising because it rules out two policies, that may look quite appealing otherwise. Namely, the social planner will never let firms equally share the second stage payoffs (as in a weak IP system with $\alpha = 0$), or implement a winner-takes-all kind of competition (as with $\alpha = 1$).

It is also easy to show that the optimum for W^e_c is

$$\hat{\alpha} = \frac{2c}{\pi} \,.$$

However, since this value is grater than what would be compatible to make collaboration an equilibrium according to proposition 1, that is:

$$\hat{\alpha} > \frac{8c^2 - \pi^2}{8c^2 + 8c\pi + \pi^2}$$

the best the social planner can do is to set α as high as the lower limit of inequality (3). This leads to the following lower bound:

Proposition 3. *Under a narrow patent protection, the lower bound of the optimal strength of the IP system is:*

$$\alpha^w \geq \frac{8c^2 - \pi^2}{8c^2 + 8c\pi + \pi^2} \,.$$

Proof. Omitted. □

The implications of this result are twofold. First, the optimal strength of the system is strictly positive. Second, it is increasing in c the marginal cost of effort. This means that, as technology becomes more complicated to develop, the system should guarantee stronger IP rights to encourage more innovation.

[**FIGURE 3 HERE**]

The curves W_c^e and W_{nc}^e do not always intersect, as shown in Figure 3. An intersection happens when c is sufficiently low (relative to π). Indeed, since the equilibrium intensity R&D is overall decreasing in the cost of effort, an increase in c would shift down both curves. However, firms tend to exert more effort in the absence of collaboration, and therefore an increase in marginal cost tends to reduce the expected payoffs more in that case. Thus, as c raises, the curve W_{nc}^e shifts down faster, and eventually W_c^2 dominates the entire curve W_{nc}^e.

4.2 Optimal Breadth

Suppose now that the patent protection is broad, in the sense that the first firm to develop the first stage innovation would enjoy exclusive IP rights also on the second stage.[11] This yields the following proposition.

Proposition 4. *Under broad patent protection, when* $\mathrm{s} \in \{(1,0),(0,1)\}$ *and there is one period left to play, firms will share their knowledge at the interim stage if and only if*

$$\alpha \leq \bar{\alpha} \tag{5}$$

[11] In the present model, this means that the firm who develop the first stage will have the bargaining to obtain $(1+\alpha)\pi$, if the second stage is achieved.

where $\bar{\alpha}$ is the first (real) root of the following equality:

$$4c^3 = \pi(1+\alpha)\left[8c^2 - \pi^2\left(1-\alpha^2\right) - \frac{\pi(1+\alpha)}{2c}\left(6c^2 - \pi^2(1-\alpha^2)\right)\right] .$$

Proof. See Appendix A. □

This proposition shows that, in order to ensure collaboration at the interim stage, only inequality (5) has to be met, because now the technological leader will obtain patent protection that extends to the next stage and will always decide to reveal its knowledge at the first stage, aiming at accelerating the development of the second stage. Accordingly, α can not be too high or too low to induce the technological leader to reveal its findings at the interim stage, because it will be able to collect higher profits at the next stage in any case. By contrast, α enters the decision of the follower to collaborate and to acquire the new knowledge. The follower anticipates that it will have to pay out royalties to the first innovator even if its R&D effort was successful and the follower was the one to develop the second stage. Thus, it may prefer to free-ride on the effort of the first innovator, unless the system is sufficiently weak (i.e., α is sufficiently low).

[**FIGURE 4 HERE**]

Even though I cannot get an explicit formula for $\bar{\alpha}$, I can still evaluate this effect numerically. Figure 4 shows the set of values (α, c) in which collaboration will arise in equilibrium under a system with broad protection. The area of collaboration is now smaller than that in the case of narrow protection (whose boundaries are denoted by the gray dashed lines).

[**FIGURE 5 HERE**]

Figure 5 shows also the welfare under broad protection with high costs. It turns out that a broad system (the black line) will never improve upon a narrow system (gray line). This is not only because a broad system does not encourage collaboration at the interim stage, but also because of the diminished effects of competition to be first to secure the IP rights.

5 Conclusion

In this paper I have examined the strategic decision to collaborate during a multi-stage R&D race by a technological leader and a follower. I examined how individual decisions are affected by the strength and the breadth of the IP regime in place, where I interpret the breadth of the patent as the stage at which the innovator is granted IP rights over the payoffs produced by the innovation, whereas the strength is simply a measure of the bargaining power of the patent holder over the entire value generated by the new technology. I show that, under a narrow patent protection, a weak system may fail to produce collaboration among innovators because it creates an incentive for the followers to free-ride on the efforts of the leaders. I also find that the optimal level of strength is never maximal, as in a winner-takes-all competition, because the presence of spillovers can encourage more R&D effort by firms. I also find that the optimal level of strength is increasing in the costliness of R&D efforts, as more complicated innovations do not need lower protection to induce more collaboration among firms. Finally, I find that a broad protection, while it may encourage disclosure, can prevent collaboration and reduce substantially the overall R&D effort exerted by firms.

The model presented is simple, but it seems robust to a number of extensions.

First note that all results hold true if we relax the assumption of a time horizon of two periods, to extend it to the case of more than two periods. The only difference would be that we have to examine more nodes or subgames, but there is no reason to believe that this will change the results substantially. Things can be quite different in a game with imperfect information about the R&D costs of the rivals. One reason is that firms may signal their types by accepting or rejecting the collaboration at the interim stage. However, this does not necessarily change the incentive for firms to postpone imitation, although it may be more costly if the other firm turns out to have very high costs for R&D. Finally, in this article I've not focused on what may happen if firms can subsidize the collaboration. This seems an interesting option to limit the scope of free-riding. However, this may raise other undesirable issues related to the competition policy, which have been already discussed in the literature.

A Derivation of Equilibria

I provide one single proof for all the results discussed in the paper.

Proof. Since there are two firms, innovation is sequential and it involves binary outcomes, there are at most 2^2 possible outcomes to consider at any subgame. Thus, I can generally write the expected payoff for each firm i when there are $l+1$ periods left to play as it follows:

$$\begin{aligned} V_i(\mathbf{s}|l+1) =& x_i[x_j V_i(s_i+1, s_j+1|l) + (1-x_j)V_i(s_i+1, s_j|l)]+ \\ &+ (1-x_i)[x_j V_i(s_i, s_j+1|l) + (1-x_j)V_i(s_i, s_j|l)] - c(x_i) \end{aligned} \tag{6}$$

Since expression (6) is concave in x_i, the first order conditions are also sufficient for an optimum. These conditions (assuming an interior solution) are:

$$\text{(7)} \qquad \frac{\partial V_i}{\partial x_i} = 0 \iff [x_j V_i(s_i+1, s_j+1|l) + (1-x_j)V_i(s_i+1, s_j|l)] + \\ - [x_j V_i(s_i, s_j+1|l) + (1-x_j)V_i(s_i, s_j|l)] = 2cx_i$$

Later, I will show that the condition $c > \pi$ is sufficient to have interior solutions. At this point, it is convenient to introduce some additional notation. Let $\delta_{i|s}(k|l)$ denote the difference in expected payoffs for firm i between innovating one stage and keeping the status quo when the other firm innovates $k \in \{0, 1\}$ steps with l periods left. That is:

$$\delta_{i|s}(k|l) = V_i(s_i+1, s_j+k|l) - V_i(s_i, s_j+k|l) \; .$$

And let $\Delta_{i|s}(l)$ denote the following difference in difference:

$$\Delta_{i|s}(l) = \delta_{i|s}(1|l) - \delta_{i|s}(0|l) \; .$$

Now we can solve the first order conditions and, by using this additional notation, we can write the Cournot-Nash equilibrium effort at any subgame as it follows:

$$\text{(8)} \qquad x^*_{i|s}(l+1) = \frac{2c \cdot \delta_{i|s}(0|l) + \Delta_{i|s}(l)\delta_{j|s}(0|l)}{4c^2 - \Delta_{i|s}(l)\Delta_{j|s}(l)} \; .$$

Now, I need to use the above definition recursively to characterize the equilibrium effort at each node of the game, and to find the sub-game perfect equilibrium. To do that, I consider narrow and broad patent protection separately.

(i) Suppose patent protection is *narrow*. When there are $l = 0$ periods left, the expected payoff for each firm i is simply:

$$(9) \qquad V_i(\mathbf{s}|l=0) = \begin{cases} 0 & \text{if } \mathbf{s} \in \{(0,0),(1,0),(0,1),(1,1)\} \\ (1+\alpha)\pi & \text{if } \mathbf{s} \in \{(2,1),(2,0)\} \\ (1-\alpha)\pi & \text{if } \mathbf{s} \in \{(1,2),(0,2)\} \\ \pi & \text{if } \mathbf{s} \in \{(2,2)\} \end{cases}$$

When there are $l = 1$ periods left, the number of stages achieved by each firm until that period can be either one or none and therefore there are 4 subgames to consider. Let consider each subgame separately.

(a) When $\mathbf{s} = (0,0)$, since firms can't achieve two stages in one period, the game ends early and firms quit doing R&D $x_{i|s=0,0}(1) = 0$. Their payoff is zero.

(b) When $\mathbf{s} = (1,1)$, firms have achieved the same number of stages (either by developing the innovation in-house or because of knowledge sharing at the interim stage) and they make their effort decision being symmetric. So we have that $\delta_{i|s=1,1}(k|0) = \delta(k|0)$ for every i. By using (9), we have:

$$\delta(0|0) = V_i(2,1|0) - V_i(1,1|0) = (1+\alpha)\pi$$

and

$$\delta(1|0) = V_i(2,2|0) - V_i(1,2|0) = \pi - (1-\alpha)\pi = \pi\alpha$$

Thus, the equilibrium effort simplifies to:

$$x^*_{i|s=1,1}(1) = \frac{\delta(0|0)(2c+\Delta(0))}{4c^2 - \Delta(0)^2} = \frac{\delta(0|0)}{2c - \delta(1|0) + \delta(0|0)} = \frac{\pi(1+\alpha)}{2c+\pi}\,.$$

(c) When $\mathbf{s} = (1,0)$, firm i is the technological leader, and firms have not shared their knowledge at the interim stage that precedes the effort decision. This implies that $\delta_{i|s=1,0}(0|0) = (1+\alpha)\pi$ and $\delta_{j|s=0,1}(k|0) = 0$ for any k. Thus, we have:

$$x^*_{i|s=1,0}(1) = \frac{\pi(1+\alpha)}{2c} \ , \quad x^*_{j|s=0,1}(1) = 0 \ .$$

(d) When $\mathbf{s} = (0,1)$, the analysis is the same as of point (c).

At this point I can easily move backwards to identify the conditions under which collaboration will occur as a subgame perfect equilibrium at the interim stage. That is, I substitute the equilibrium efforts into the expected payoffs (6) to obtain:

$$(10) \qquad V_i(\mathbf{s}|l=1) = \begin{cases} 0 & \text{if } \mathbf{s} \in \{(0,0)\} \\ \frac{\pi^2(1+\alpha)^2}{4c} & \text{if } \mathbf{s} \in \{(1,0)\} \\ \frac{\pi^2(1+\alpha)(1-\alpha)}{2c} & \text{if } \mathbf{s} \in \{(0,1)\} \\ \frac{\pi^2(1+\alpha)[c(3-\alpha)+\pi(1-\alpha)]}{(2c+\pi)^2} & \text{if } \mathbf{s} \in \{(1,1)\} \end{cases}$$

Then, moving back to the interim stage, collaboration is a sub-game perfect equilibrium if and only if $\mathbf{s} \in \{(0,1),(1,0)\}$ and

$$V_i(1,1|1) \geq \max\{V_i(0,1|1), V_i(1,0|1)\} \ .$$

By using (10), the above condition becomes the inequality (**??**) of proposition (**??**) that I report here for convenience:

$$\frac{8c^2 - \pi^2}{8c^2 + 8c\pi + \pi^2} \geq \alpha \geq \frac{-2c^2 + 2c\pi + \pi^2}{2c^2 + 2c\pi + \pi^2} \ .$$

Proceeding backwards, when there are $l = 2$ periods left to play, we have only one subgame to consider because s $\in \{(0,0)\}$. In this case, firms are symmetric and so we have:

$$x^*_{i|s=0,0}(2) = \frac{\delta(0|1)}{2c - \delta(1|1) + \delta(0|1)}$$

However, we have to distinguish cases in which α is set in a way to induce collaboration, or not. In particular, we have that:

$$\delta(0|1) = \begin{cases} V_i(1,1|1) & \text{if (3) is satisfied} \\ V_i(1,0|1) & \text{otherwise} \end{cases}$$

and

$$\delta(1|1) = \begin{cases} 0 & \text{if (3) is satisfied} \\ V_i(1,1|1) - V_i(0,1|1) & \text{otherwise} \end{cases}$$

Notice that the effort when there's collaboration is higher than when collaboration is expected at the second period. Thus, we can rewrite the equilibrium effort at this period as it follows:

$$x^*_{i|s=0,0}(2) = \max\left\{\frac{V_i(1,1|1)}{2c + V_i(1,1|1)}, \frac{V_i(1,0|1)}{2c + V_i(1,1|1) - V_i(0,1|1) + V_i(1,0|1)}\right\}$$

(ii) Suppose now that patent protection is *Broad*. The main difference with tha narrow case is that the firm who obtained patent protection at the first stage—the patent holder—is now entitled a larger fraction of payoffs when the second-stage is achieved. Let $\hat{i}$ denote the patent holder.

When there are $l = 0$ periods left, the expected payoff for firm i is simply:

(11)

$$V_i(\mathbf{s}|l=0) = \begin{cases} 0 & \text{if } \mathbf{s} \in \{(0,0),(1,0),(0,1),(1,1)\} \\ (1+\alpha)\pi & \text{if } \mathbf{s} \in \{(2,1),(2,0),(1,2),(0,2),(2,2)\} \text{ and } i = \hat{i} \\ (1-\alpha)\pi & \text{if } \mathbf{s} \in \{(2,1),(2,0),(1,2),(0,2),(2,2)\} \text{ and } i \neq \hat{i} \end{cases}$$

When there are $l = 1$ periods left, there are again four subgames to consider:

(a) When $s \in \{(0,0),(0,1),(1,0)\}$ the analysis is the same as for the case of narrow protection (i.e., points (a), (b) and (d)), except that $i : s_i > s_j$ files for patent protection.

(b) When $s = (1,1)$, firms have symmetric knowledge but their payoffs are asymmetric because one firm $\hat{i}$ has been granted broad patent protection (recall if both firms achieved the first stage after one period, the patent is granted at random to one of the firms). Then we have:

$$\delta_{i|s=1,1}(0|1) = \begin{cases} (1+\alpha)\pi & \text{if } i = \hat{i} \\ (1-\alpha)\pi & \text{if } i \neq \hat{i} \end{cases}$$

and $\delta_{i|s=1,1}(1|1) = 0$ for every i. Accordingly, we have:

$$x_{i|s=1,1}(1)^{**} = \frac{\pi}{4c^2 - (1-\alpha^2)\pi^2} \begin{cases} (1+\alpha)[2c - (1-\alpha)\pi] & \text{if } i = \hat{i} \\ (1-\alpha)[2c - (1+\alpha)\pi] & \text{if } i \neq \hat{i} \end{cases}$$

Then, the expected payoffs are:

(12) $$V_i(\mathbf{s}|l=1) =$$

$$\begin{cases} 0 & \text{if s} \in \{(0,0)\} \\ \frac{\pi^2(1+\alpha)^2}{4c} & \text{if s} \in \{(1,0)\} \\ \frac{\pi^2(1+\alpha)(1-\alpha)}{2c} & \text{if s} \in \{(0,1)\} \\ \frac{\pi^2(1+\alpha)\left[4c^3(3-\alpha)-c\pi^2(1-\alpha)^2(1+\alpha)-8c^2\pi\left(1-\alpha^2\right)-\pi^3\left(1-\alpha^2\right)^2\right]}{(4c^2-\pi^2(1-\alpha^2))^2} & \text{if s} \in \{(1,1)\} \text{ and } i=\hat{i} \\ \frac{\pi^2(1-\alpha)\left[4c^3(3+\alpha)-c\pi^2(1-\alpha)(1+\alpha)^2-8c^2\pi\left(1-\alpha^2\right)+\pi^3\left(1-\alpha^2\right)^2\right]}{(4c^2-\pi^2(1-\alpha^2))^2} & \text{if s} \in \{(1,1)\} \text{ and } i \neq \hat{i} \end{cases}$$

Moving back to the interim stage, although it might seem not so immediate to check it, it is however obvious that firm i will always decide to make its technology freely available to the rival, as it raises expected profits. Thus, collaboration in research at this stage will occur if and only if s $\in \{(1,0),(0,1)\}$ and:

$$V_{i\neq\hat{i}}(1,1|1) \geq V_{i\neq\hat{i}}(0,1|1)\ .$$

The above condition gives inequality (5)of proposition (4) reported here:

$$2c^3 + \frac{\pi^2(1+\alpha)^2}{4c}[6c^2 - \pi^2(1-\alpha^2)] \geq \frac{\pi(1+\alpha)}{2}\left(8c^2 - \pi^2\left(1-\alpha^2\right)\right)$$

which unfortunately can not be easily decomposed to highlight the role of α (but I do that graphically in the main text of the paper).

When there are $l = 2$ periods left to play, firms are symmetric and $s = (0,0)$. In this case, firms are symmetric but we have to distinguish cases in which α is set in a way to induce collaboration, or not. In particular, we have that:

$$\delta(0|1) = \begin{cases} V_{\hat{i}}(1,1|1) & \text{if (5) is satisfied} \\ V_i(1,0|1) & \text{otherwise.} \end{cases}$$

We also have that:

$$\delta(1|1) = \begin{cases} \left[V_{\hat{i}}(1,1|1) - V_{i\neq\hat{i}}(1,1|1)\right]/2 & \text{if (5) is satisfied} \\ \left[V_{\hat{i}}(1,1|1) + V_{i\neq\hat{i}}(1,1|1)\right]/2 - V_i(0,1|1) & \text{otherwise.} \end{cases}$$

Accordingly, the equilibrium effort at this period is:

$$x_{i|s=0,0}(2)^{**} = \begin{cases} \frac{V_{\hat{i}}(1,1|1)}{2c+[V_{\hat{i}}(1,1|1)+V_{\hat{i}}(1,1|1)]/2} & \text{if (5) is satisfied} \\ \frac{V_i(1,0|1)}{2c-[V_{\hat{i}}(1,1|1)+V_{\hat{i}}(1,1|1)]/2-V_i(0,1|1)+V_i(1,0|1)} & \text{otherwise.} \end{cases}$$

□

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B Figures

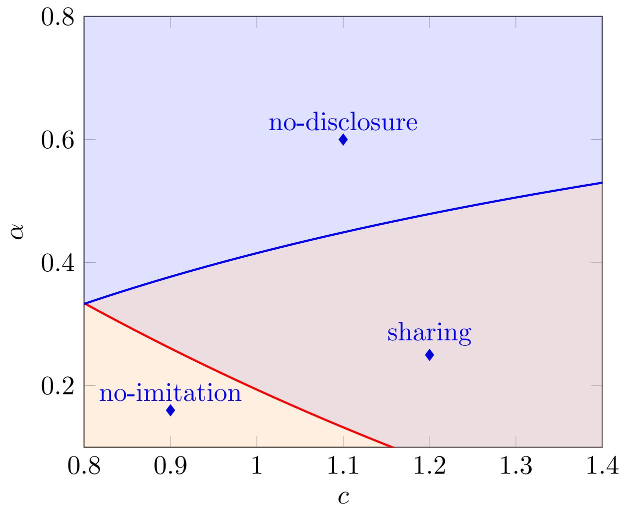

Figure 1: Collaboration under Narrow Patent Protection ($\pi = .99$)

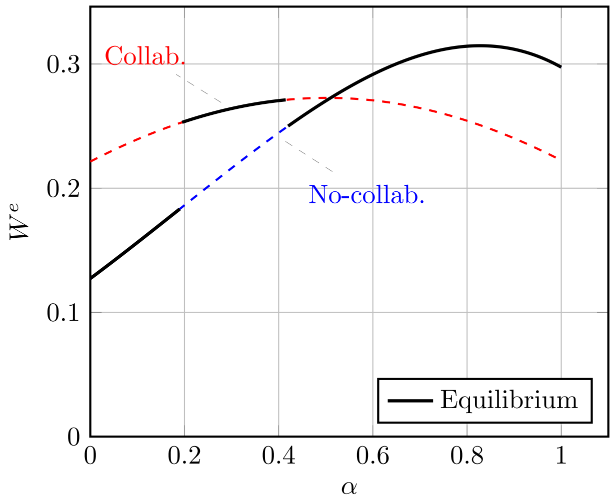

Figure 2: Ex-ante Welfare Under Narrow Patent Protection ($\pi = .99, c = 1$)

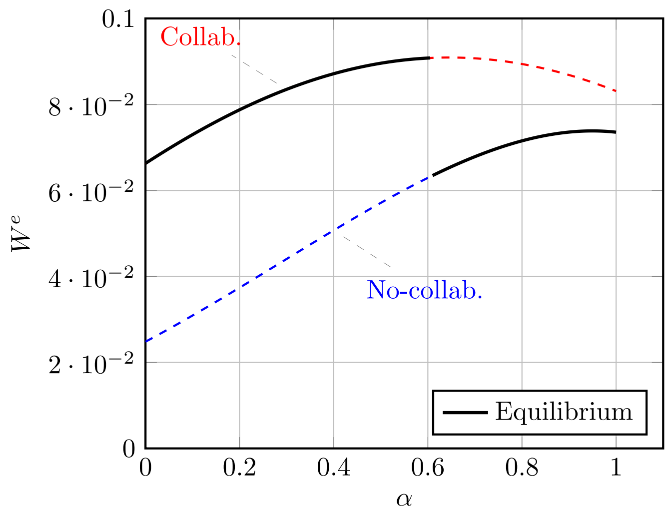

Figure 3: Ex-ante Welfare Under Narrow Patent Protection with High Costs ($\pi = .99, c = 1.8$)

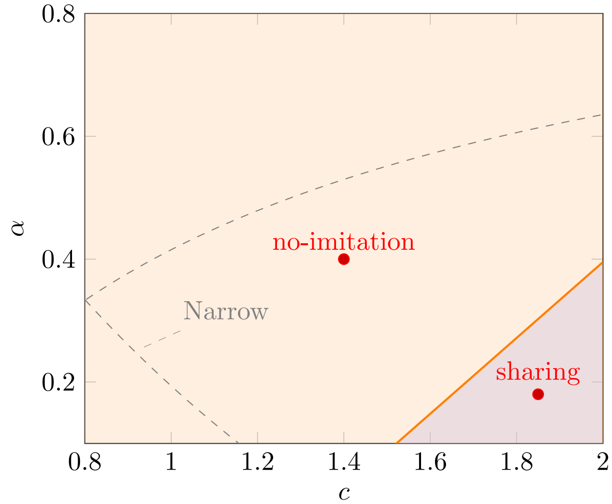

Figure 4: Collaboration under Broad Patent Protection ($\pi = .99$)

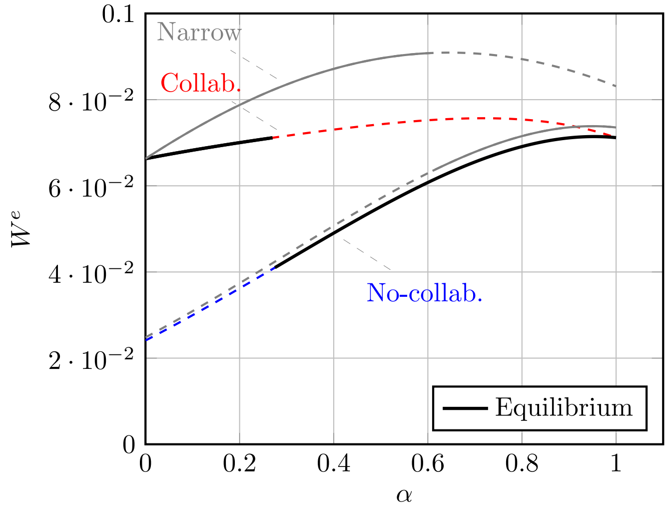

Figure 5: Welfare Under Broad Patent Protection With High Costs ($\pi = .99, c = 1.8$)