

## Experimentation, Patents, and Innovation<sup>†</sup>

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*This paper studies a simple model of experimentation and innovation. Our analysis suggests that patents improve the allocation of resources by encouraging rapid experimentation and efficient ex post transfer of knowledge. Each firm receives a signal on the success probability of a project and decides when to experiment. Successes can be copied. First, we assume that signal qualities are the same. Symmetric equilibria involve delayed and staggered experimentation, whereas the optimal allocation never involves delays and may involve simultaneous experimentation. Appropriately designed patents implement the optimal allocation. Finally, we discuss the case when signals differ and are private information. (JEL D82, D83, O31, O33, O34)*

Most modern societies provide intellectual property rights protection to innovators using a patent system. The main argument in favor of patents is that they encourage *ex ante* innovation by creating *ex post* monopoly rents (e.g., Kenneth J. Arrow 1962; Edmund W. Kitch 1977; Jennifer F. Reinganum 1981; Jean Tirole 1988; Richard Gilbert and Carl Shapiro 1990; Paul Klemperer 1990; Paul M. Romer 1990; Gene M. Grossman and Elhanan Helpman 1991; Philippe Aghion and Peter Howitt 1992; Suzanne Scotchmer 1999; Nancy Gallini and Scotchmer 2002). In this paper, we suggest an alternative (and complementary) social benefit to patents. We show that, under certain circumstances, patents encourage experimentation by potential innovators while still allowing socially beneficial transmission of knowledge across firms.

We construct a stylized model of experimentation and innovation. In our baseline game,  $N$  symmetric potential innovators (firms) have each access to a distinct research opportunity and a private signal on how likely it is to result in a successful innovation. Firms can decide to experiment at any point in time. A successful innovation is publicly observed and can be copied by any of the other potential innovators (for example, other firms can build on the knowledge revealed by the innovation in order to increase their own probability of success, but in the process capture some of the rents of this first innovator). The returns from the implementation of a successful innovation are

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nonincreasing in the number of firms implementing it. We provide an explicit characterization of the equilibria of this dynamic game. The symmetric equilibrium always features delayed and staggered experimentation. In particular, experimentation does not take place immediately, and involves one firm experimenting before others (and the latter firms free-riding on the former's experimentation). In contrast, the optimal allocation never involves delays and may require simultaneous rather than staggered experimentation. The insufficient equilibrium incentives for experimentation may create a significant efficiency loss: the ratio of social surplus generated by the equilibrium relative to the optimal allocation can be arbitrarily small.

We next show that a simple arrangement resembling a patent system, where a copying firm has to make a prespecified payment to the innovator, can implement the optimal allocation (and in the rest of the paper, we refer to this arrangement as a "patent system"). When the optimal allocation involves simultaneous experimentation, the patent system makes free-riding prohibitively costly and implements the optimal allocation as the unique equilibrium. When the optimal allocation involves staggered experimentation, the patent system plays a more subtle role. It permits *ex post* transmission of knowledge but still increases experimentation incentives to avoid delays. The patent system can achieve this because it generates "conditional" transfers. An innovator receives a patent payment only when copied by other firms. Consequently, patents encourage one firm to experiment earlier than others, thus achieving rapid experimentation without sacrificing useful transfer of knowledge. Moreover, we show that patents can achieve this outcome in all equilibria. The fact that patents are particularly well designed to play this role is also highlighted by our result that while an appropriately designed patent implements the optimal allocation in all equilibria, subsidies to experimentation, research, or innovation cannot achieve the same objective.

In our baseline model, both the optimal allocation and the symmetric equilibrium involve sequential experimentation. Inefficiency results from lack of sufficient experimentation or from delays. The structure of equilibria is richer when the strength (quality) of the signals received by potential innovators differs and is also private information. In this case, those with sufficiently strong signals will prefer not to copy successful innovations. We show that in this more general environment, patents are, again, potentially useful (though they cannot typically achieve the optimal allocation).

Although our analysis is purely theoretical, we believe that the insights it generates, in particular regarding the role of patents in discouraging delay in research and encouraging experimentation, are relevant for thinking about the role of the patent systems in practice. Two assumptions are important for our results. The first is that pursuing an unsuccessful research line makes a subsequent switch to an alternative line more costly. We impose this feature in the simplest possible way, assuming that such a switch is not possible, though our qualitative results would not be affected if switching were feasible but costly. We view this assumption as a reasonable approximation to reality. Commitment of intellectual and financial resources to a specific research line or vision is necessary for success, and once such commitment has been made, changing course is not easy.<sup>1</sup> Our second key assumption is that copying of

<sup>1</sup>For example, in the computer industry, firms such as Digital Equipment Corporation (DEC) that specialized in mainframes found it difficult to make a successful switch to personal computers (e.g., Alan R. Earls 2004). Similarly,

successful projects is possible (without prohibitive patents) and reduces the returns to original innovators. This assumption also appears quite plausible. Copying of a successful project here should be interpreted more broadly as using the information revealed by successful innovation or experimentation, so it does not need to correspond to replicating the exact same innovation (or product),<sup>2</sup> and naturally such copying will have some negative effect on the returns of the original innovator.

In addition to the literature on patents mentioned above, a number of other works are related to our paper. First, ours is a simple model of (social) experimentation and shares a number of common features with recent work in this area (e.g., Patrick Bolton and Christopher Harris 1999; and Godfrey Keller, Sven Rady, and Martin Cripps 2005). These papers characterize equilibria of multi-agent two-armed bandit problems and show that there may be insufficient experimentation. The structure of the equilibrium is particularly simple in our model and can be characterized explicitly because all payoff-relevant uncertainty is revealed after a single successful experimentation. In addition, as discussed above, there is insufficient experimentation in our model as well, though this also takes a simple form: either there is free-riding by some firms reducing the amount of experimentation, or experimentation is delayed. We also show that patent systems can increase experimentation incentives and implement the optimal allocation.

Second, the structure of equilibria with symmetric firms is reminiscent to equilibria in war of attrition games (e.g., J. Maynard Smith 1974; Ken Hendricks, Andrew Weiss, and Charles A. Wilson 1988; John Haigh and Chris Cannings 1989). War of attrition games have been used in various application domains, such as the study of market exit (Drew Fudenberg and Tirole 1986; Jeremy Bulow and Klemperer 1994), research tournaments (Curtis R. Taylor 1995), auctions (Bulow and Klemperer 1999), investment choices (Christophe Chamley and Douglas Gale 1994), exploratory drilling (Hendricks and Dan Kovenock 1989; Hendricks and Robert H. Porter 1996) and the diffusion of new technologies (Sandeep Kapur 1995). Similar in spirit with our work, Partha Dasgupta (1988) discusses *waiting games* of technological change, in which there is a late-mover advantage due to knowledge spillovers. In our symmetric model, as in symmetric wars of attrition, players choose the stochastic timing of their actions in such a way as to make other players indifferent and willing to mix over the timing of their own actions. The structure of equilibria and the optimal allocation is different, however, and the optimal allocation may involve either simultaneous experimentation by all players or staggered experimentation similar to that resulting in asymmetric equilibria. The novel beneficial role of patents in our model arises from their ability to implement such asymmetric equilibria.

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early innovators in the cell phone industry, such as Nokia and Ericsson, appear to be slow in switching to the new generation of more advanced wireless devices and smartphones, and have been generally lagging behind companies such as Apple and RIM. Another interesting example comes from the satellite launches. The early technology choice for launching satellites into space relied on large ground-based rockets. Despite evidence that using smaller rockets and carrying these to the upper atmosphere using existing aerospace equipment would be considerably cheaper and more flexible, organizations such as NASA have not switched to this new technology, while private space technology companies have (see Tim Harford 2009).

<sup>2</sup>In terms of the examples in footnote 1, while DEC, Nokia, and Ericsson may have been slow in adopting new technologies, several other new companies have built on the technological advances that took place in personal computers and smartphones.

Finally, the monotonicity property when the quality of signals differs across agents is similar to results in generalized wars of attrition (e.g., Fudenberg and Tirole 1986; Bulow and Klemperer 1994; Bulow and Klemperer 1999) and is also related to Faruk Gul and Russell Lundholm (1995) result on the clustering of actions in herding models. In the context of a standard herding model with endogenous timing, Gul and Lundholm construct an equilibrium in which agents with stronger signals act earlier than those with weaker signals, though the specifics of our model and analysis differs from these previous contributions.<sup>3</sup>

The rest of the paper is organized as follows. In Section I, we describe our baseline model with two symmetric firms. We provide an explicit characterization of both the asymmetric and symmetric equilibria in this model. Section II extends these results to a setup with an arbitrary number of firms. Section III characterizes the optimal allocation and shows that the efficiency gap between the symmetric equilibrium and the optimal allocation can be arbitrarily large. The analysis in this section also demonstrates that an appropriately designed patent system can implement the optimal allocation (in all equilibria). Section IV extends the model to an environment with two firms that have different signal qualities. Section V concludes, while the Appendix contains additional results and some of the proofs omitted from the text.

## I. Two Symmetric Firms

### A. Environment

The economy consists of two research firms, each maximizing the present discounted value of profits. Time is continuous and both firms discount the future at a common rate  $r > 0$ .

Each firm can implement (“experiment with”) a distinct project. The success probability of experimentation is  $p > 0$ . The success or failure of experimentation by a firm is publicly observed. When experimentation is successful, we refer to this as an “innovation.”

At time  $t$ , a firm can choose one of three possible actions: experiment with a project (in particular, with the project on which the firm has received a positive signal); copy a successful project; and wait. Experimentation and copying are irreversible, so that a firm cannot then switch to implement a different project. In the context of research, this captures the fact that commitment of intellectual and financial resources to a specific research line or project is necessary for success. Copying of a successful project can be interpreted more broadly as using the information revealed by successful innovation or experimentation, so it does not need to correspond to the second firm replicating the exact same innovation (or product).<sup>4</sup>

<sup>3</sup>This monotonicity property does not hold in our model when there are more than two firms and the support of signals includes sufficiently strong signals so that some firms prefer not to copy successful experimentations as is shown in Appendix B.

<sup>4</sup>Several generalizations do not affect our qualitative results, and are not introduced to reduce notation and maximize transparency. These include: copying can be successful with some probability  $\nu \in (p, 1]$ ; (copying after an unsuccessful experimentation is feasible, but involves a cost  $\Gamma_1 > 0$ ; and experimentation itself involves a cost  $\Gamma_2 > 0$ ).

Payoffs depend on the success of the project and whether the project is copied. During an interval of length  $\tau$ , the payoff to a firm that is the only one implementing a successful project is  $\pi_1\tau > 0$ . In contrast, if a successful project is implemented by both firms, each receives  $\pi_2\tau > 0$ .<sup>5</sup> The payoff to an unsuccessful project is normalized to zero.

Until we introduce heterogeneity in success probabilities, we maintain the following assumption.<sup>6</sup>

ASSUMPTION 1:

$$\pi_1 > \pi_2 > p\pi_1.$$

Let us also define the present discounted value of profits as

$$\Pi_j \equiv \frac{\pi_j}{r} \text{ for } j = 1, 2,$$

and for future reference, define

$$(1) \quad \beta \equiv \frac{\Pi_2}{\Pi_1}.$$

Clearly,  $\beta \in (p, 1)$  in view of Assumption 1. Assumption 1 implies that the payoff from a new innovation is decreasing in the number of firms that adopt it ( $\pi_1 > \pi_2$ ) and also that the expected payoff of a firm's experimentation is smaller than the payoff from copying a successful innovation. In particular, the firm prefers to copy than to experiment with its own research opportunity.

Now we are in a position to define strategies in this game. Let a history up to time  $t$  be denoted by  $h^t$ . The set of histories is denoted by  $\mathcal{H}^t$ . A strategy for a firm is a mapping from time  $t$  and the history of the game up to  $t$ ,  $h^t$ , to the *flow rate of experimentation* at time  $t$  and the distribution over projects. Thus, the time  $t$  strategy can be written as

$$\sigma : \mathbb{R}_+ \times \mathcal{H}^t \rightarrow \bar{\mathbb{R}}_+ \times \Delta(\{1, 2\}),$$

where  $\mathbb{R}_+ \equiv \mathbb{R}_+ \cup \{+\infty\}$  and  $\Delta(\{1, 2\})$  denotes the set of probability distributions over the set of projects (project available to the first, second firm is labeled 1, 2 respectively), corresponding to the choice of project when the firm implements one. The latter piece of generality is largely unnecessary (and will be omitted), since there will never be mixing over projects (a firm will either copy a successful

<sup>5</sup>It will be evident from the analysis below that all of our results can be straightforwardly generalized to the case where an innovator receives payoff  $\pi_2^{\text{first}}\tau$  when copied, whereas the copier receives  $\pi_2^{\text{second}}\tau$ . Since this has no major effect on the main economic insights and just adds notation, we do not pursue this generalization.

<sup>6</sup>The structure of equilibria without this assumption is trivial as our analysis in Section III shows.

project or experiment with the project for which it has received a positive signal). Here  $\sigma(t, h^t) = (0, \cdot)$  corresponds to waiting at time  $t$  and  $\sigma(t, h^t) = (\infty, j)$  corresponds to implementing project  $j$  at time  $t$ , which could be experimentation or copying of a successful project. Let us also denote the strategy of firm  $i = 1, 2$  by  $\sigma_i = \{\sigma_i(t, \cdot)\}_{t=0}^\infty$ .

History up to time  $t$  can be summarized by two events  $a^t \in \{0, 1\}$  denoting whether the other firm has experimented up to time  $t$  and  $s^t \in \{0, 1\}$  denoting whether this choice was successful. With a slight abuse of notation we will use both  $\sigma(t, h^t)$  and  $\sigma(t, a^t, s^t)$  to denote time  $t$  strategies. We study subgame perfect equilibria in the environment defined above. In particular, a subgame perfect equilibrium (or simply *equilibrium*) is a strategy profile  $(\hat{\sigma}_1, \hat{\sigma}_2)$  such that  $(\hat{\sigma}_1|h^k, \hat{\sigma}_2|h^k)$  is a Nash equilibrium of the subgame defined by history  $h^t$  for all histories  $h^t \in \mathcal{H}^t$ , where  $\hat{\sigma}_i|h^k$  denotes the restriction of  $\hat{\sigma}_i$  to the histories consistent with  $h^k$ .

### B. Asymmetric Equilibria

Even though firms are symmetric (in terms of their payoffs and information), there can be symmetric and asymmetric equilibria. Our main interest is with symmetric equilibria, where strategies are independent of the identity of the player. Nevertheless, it is convenient to start with asymmetric equilibria. These equilibria are somewhat less natural, because, as we will see, they involve one of the players never experimenting until the other one does. Before describing the equilibria, we introduce some additional notation. In particular, the flow rate of experimentation  $\sigma$  induces a stochastic distribution of “stopping time,” which we denote by  $\tau$ . The stopping time  $\tau$  designates the probability distribution that experimentation will happen at any time  $t \in \overline{\mathbb{R}}_+$  conditional on the other player not having experimented until then. A pure strategy simply specifies  $\tau \in \overline{\mathbb{R}}_+$ . For example, the strategy of experimenting immediately is  $\tau = 0$ , whereas that of waiting for the other firm’s experimentation is represented by  $\tau = +\infty$ . The  $\tau$  notation is convenient to use for the next two propositions, while in characterizing the structure of equilibria we need to use  $\sigma$  (thus justifying the introduction of both notations).<sup>7</sup>

In an asymmetric equilibrium, one of the firms, say 1, experiments immediately with its research project. Firm 2 copies firm 1 immediately afterward if the latter is successful and tries its own project otherwise. Throughout the paper, when there are two firms, we use the notation  $\sim i$  to denote the firm  $i' \neq i$ .

**PROPOSITION 1:** *Suppose that Assumption 1 holds. Then there exist two asymmetric equilibria. In each equilibrium,  $\tau_i = 0$  and  $\tau_{\sim i} = +\infty$  for  $i = 1, 2$ .*

<sup>7</sup> Here we could follow the more precise approach in Leo K. Simon and Maxwell B. Stinchcombe (1989) for modeling strategies in continuous-time games with jumps. This amounts to defining an extended strategy space, where stopping times are defined for all  $t \in \overline{\mathbb{R}}_+$  and also for  $t+$  for any  $t \in \mathbb{R}_+$ . In other words, strategies will be piecewise continuous and right continuous functions of time, so that a jump immediately following some time  $t \in \mathbb{R}_+$  is well defined. Throughout, we do allow such jumps, but do not introduce the additional notation, since this is not necessary for any of the main economic insights or proofs.



The proof of the proposition is straightforward and can therefore be omitted. Note that the equilibria described above are not the only asymmetric equilibria in this environment. Another set of such equilibria involves one of the firms experimenting with positive probability (not going to zero) at time  $t = 0$  and both firms using a constant flow of experimentation from then on. The crucial feature of asymmetric equilibria is that they explicitly condition on the identity of the firms.

### C. Symmetric Equilibria

As mentioned above, asymmetric equilibria explicitly condition on the identity of the firm: one of the firms, with label  $i$ , is treated differently than the firm with label  $\sim i$ . This has important payoff consequences. In particular, it can be verified easily that firm  $\sim i$  has strictly greater payoffs in the equilibrium of Proposition 1 than firm  $i$ . In addition, as already noted in the previous section, asymmetric equilibria rely on some degree of coordination between the firms, e.g., one of them will not experiment until the other one does. In this light, symmetric equilibria, where strategies are not conditioned on firms' "labels," and firms obtain the same equilibrium payoffs in expectation are more natural. In this subsection, we study such symmetric equilibria.

As defined above, a firm's strategy is a mapping from time and the firm's information set to the flow rate of experimentation with a project. We refer to a strategy as pure if the flow rate of experimentation at a given time  $t$  is either 0 or  $\infty$ . Our first result shows that there are no pure-strategy symmetric equilibria.

**PROPOSITION 2:** *Suppose that Assumption 1 holds. Then there exist no symmetric pure-strategy equilibria.*

**PROOF:**

Suppose, to obtain a contradiction, that a symmetric pure-strategy equilibrium exists. Then  $\tau^* = t \in \mathbb{R}_+$  for  $i = 1, 2$ , yielding payoff

$$V(\tau^*, \tau^*) = e^{-rt} p \Pi_1$$

to both players. Now consider a deviation  $\tau' > t$  for one of the firms, which involves waiting for a time interval  $\epsilon$  and copying a successful innovation if there is such an innovation during this time interval. As  $\epsilon \rightarrow 0$ , this strategy gives the deviating firm payoff equal to

$$V(\tau', \tau^*) = \lim_{\epsilon \downarrow 0} e^{-r(t+\epsilon)} \left[ p \Pi_2 + (1 - p) p \Pi_1 \right],$$

since with probability  $p$  the other firm experiments successfully and the deviating firm simply copies the innovation (first term in the brackets) and with probability  $1 - p$  the experimentation is unsuccessful, in which case the deviating firm experiments on its own and obtains monopoly profits with probability  $p$  (second term in the brackets). Assumption 1 implies that  $V(\tau', \tau^*) > V(\tau^*, \tau^*)$ , establishing the result.

Proposition 2 is intuitive. Asymmetric equilibria involve one of the firms always waiting for the other one to experiment and receiving higher payoff. Intuitively, Proposition 2 implies that in symmetric equilibria both firms would like to be in the position of the firm receiving higher payoffs and thus delaying their own experimentation in order to benefit from that of the other firm. These incentives imply that no (symmetric) equilibrium can have immediate experimentation with probability 1 by either firm.

Proposition 2 also implies that all symmetric equilibria must involve mixed strategies. Moreover, any candidate equilibrium strategy must involve copying of a successful project in view of Assumption 1 and immediate experimentation when the other firm has experimented unsuccessfully. Therefore, we can restrict attention to time  $t$  strategies of the form

$$(2) \quad \hat{\sigma}_i(t, a^t, s^t) = \begin{cases} (1, \sim i) & \text{if } a^t = 1 \text{ and } s^t = 1, \\ (1, i) & \text{if } a^t = 1 \text{ and } s^t = 0, \\ (\lambda(t), i) & \text{if } a^t = 0, \end{cases}$$

where  $\lambda : \mathbb{R}_+ \rightarrow \bar{\mathbb{R}}_+$  designates the flow rate of experimentation at time  $t$  conditional on no experimentation by either firm up to time  $t$ . Given this observation, from now on we will work directly with  $\lambda(t)$ .

Next we derive an explicit characterization of the (unique) symmetric equilibrium. The next lemma (proof in the Appendix) shows that symmetric equilibria must involve mixing on all  $t \in \mathbb{R}_+$  and will be used in the characterization of mixed-strategy equilibria.

LEMMA 1: *The support of mixed strategy equilibria is  $\mathbb{R}_+$ .*

Lemma 1 implies that in all symmetric equilibria there will be mixing at all times (until there is experimentation). Using this observation, Proposition 3 symmetric equilibrium in continuous time characterizes the unique symmetric equilibrium. Let us illustrate the reasoning here by assuming that firms use a constant flow rate of experimentation (the proof of Proposition 3 symmetric equilibrium in continuous time relaxes this assumption). In particular, suppose that firm  $\sim i$  innovates at the flow rate  $\lambda$  for all  $t \in \mathbb{R}_+$ . Then the value of innovating at time  $t$  (i.e., choosing  $\tau = t$ ) for firm  $i$  is

$$(3) \quad V(t) = \int_0^t \lambda e^{-\lambda z} e^{-rz} [p\Pi_2 + (1 - p)p\Pi_1] dz + e^{-\lambda t} e^{-rt} p\Pi_2.$$

This expression uses the fact that when firm  $\sim i$  is experimenting at the flow rate  $\lambda$ , the timing of its experimentation has an exponential distribution, with density  $\lambda e^{-\lambda t}$ . Then the first term in (3) is the expected discounted value from the experimentation of firm  $\sim i$  between 0 and  $t$  (again taking into account that following an experimentation, a successful innovation will be copied, with continuation value  $p\Pi_2 + (1 - p)p\Pi_1$ ). The second term is the probability that firm  $\sim i$  does not experiment



until  $t$ , which, given the exponential distribution, is equal to  $e^{-\lambda t}$ , multiplied by the expected discounted value to firm  $i$  when it is the first to experiment at time  $t$  (given by  $e^{-rt}p\Pi_2$ ).

Lemma 1 implies that  $V(t)$  must be constant in  $t$  for all  $t \in \mathbb{R}_+$ . Therefore, its derivative  $V'(t)$  must be equal to zero for all  $t$  in any symmetric equilibrium implying that

$$(4) \quad V'(t) = \lambda e^{-\lambda t} e^{-rt} [p\Pi_2 + (1 - p)p\Pi_1] - (r + \lambda) e^{-\lambda t} e^{-rt} p\Pi_2 = 0,$$

for all  $t$ . This equation has a unique solution:

$$(5) \quad \lambda^* \equiv \frac{r\beta}{1 - p} \text{ for all } t.$$

The next proposition shows that this result also holds when both firms can use time-varying experimentation rates.

**PROPOSITION 3:** *Suppose that Assumption 1 holds. Then there exists a unique symmetric equilibrium. This equilibrium involves both firms using a constant flow rate of experimentation  $\lambda^*$  as given by (5). Firm  $i$  immediately copies a successful innovation by firm  $\sim i$  and experiments if firm  $\sim i$  experiments unsuccessfully.*

**PROOF:**

Suppose that firm  $\sim i$  experiments at the flow rate  $\lambda(t)$  at time  $t \in \mathbb{R}_+$ . Let us define

$$(6) \quad m(t) = \int_0^t \lambda(z) dz.$$

Then the equivalent of (3) is

$$(7) \quad V(t) = \int_0^t \lambda(z) e^{-m(z)} e^{-rz} [p\Pi_2 + (1 - p)p\Pi_1] dz + e^{-m(t)} e^{-rt} p\Pi_2.$$

Here  $\int_{t_1}^{t_2} \lambda(z) e^{-m(z)} dz$  is the probability that firm  $\sim i$  (using strategy  $\lambda$ ) will experiment between times  $t_1$  and  $t_2$ , and  $e^{-m(t)} = 1 - \int_0^t \lambda(z) e^{-m(z)} dz$  is the probability that  $\sim i$  has not experimented before time  $t$ . Thus the first term is the expected discounted value from the experimentation of firm  $\sim i$  between 0 and  $t$  (discounted and multiplied by the probability of this event). The second term is again the probability that firm  $\sim i$  does not experiment until  $t$  multiplied by the expected discounted value to firm  $i$  when it is the first to experiment at time  $t$  (given by  $e^{-rt}p\Pi_2$ ).

Lemma 1 implies that  $V(t)$  must be constant in  $t$  for all  $t \in \mathbb{R}_+$ . Since  $V(t)$  is differentiable in  $t$ , this implies that its derivative  $V'(t)$  must be equal to zero for all  $t$ . Therefore,

$$\begin{aligned} V'(t) &= \lambda(t)e^{-m(t)}e^{-rt}[p\Pi_2 + (1 - p)p\Pi_1] - (r + m'(t))e^{-m(t)}e^{-rt}p\Pi_2 \\ &= 0 \text{ for all } t. \end{aligned}$$

Moreover, note that  $m(t)$  is differentiable and  $m'(t) = \lambda(t)$ . Therefore, this equation is equivalent to

$$(8) \quad \lambda(t)[p\Pi_2 + (1 - p)p\Pi_1] = (r + \lambda(t))p\Pi_2 \text{ for all } t.$$

The unique solution to (8) is (5), establishing the uniqueness of the symmetric equilibrium without restricting strategies to constant flow rates.

We end this section by discussing how the equilibrium flow rate of experimentation  $\lambda^*$ , given by equation (5), is affected by the relevant parameters. In particular, consider increasing  $\pi_1$  (the inequality  $\pi_2 > p\pi_1$  would clearly continue to hold). This increases the value of waiting for a firm and leaves the value of experimenting unchanged, so the equilibrium flow rate of experimentation declines, i.e., increasing  $\pi_1$  reduces  $\beta$  and  $\lambda^*$ .

## II. Multiple Firms

Let us now suppose that there are  $N$  firms, each of which receives a positive signal about one of the projects. The probability that the project that has received a positive signal will succeed is still  $p$  and each firm receives a signal about a different project. Let  $\pi_n$  denote the flow payoff from a project that is implemented by  $n$  other firms and define

$$\Pi_n \equiv \frac{\pi_n}{r}.$$

Once again,  $\beta \equiv \Pi_2/\Pi_1$  as specified in (1) and Assumption 1 holds, so that  $\beta > p$ .

The following proposition is established using similar arguments to those in the previous section and its proof is omitted.

**PROPOSITION 4:** *Suppose that Assumption 1 holds and that there are  $N \geq 2$  firms. Then there exist no symmetric pure-strategy equilibria. Moreover the support of the mixed-strategy equilibria is  $\mathbb{R}_+$ .*

It is also straightforward to show that there exist asymmetric pure-strategy equilibria. For example, when  $\Pi_N/\Pi_1 > p$ , it is an equilibrium for firm 1 to experiment and the remaining  $N - 1$  to copy if this firm is successful. If it is unsuccessful, then firm 2 experiments, and so on.

As in the previous section, symmetric equilibria are of greater interest. To characterize the structure of symmetric equilibria, let us first suppose that

$$(9) \quad \Pi_n = \Pi_2 \text{ for all } n \geq 2$$

and also to simplify the discussion, focus on symmetric equilibria with constant flow rates. In particular, let the rate of experimentation when there are  $n \geq 2$  firms be  $\lambda_n$ . Consider a subgame starting at time  $t_0$  with  $n$  firms that have not yet experimented (and all previous,  $N - n$ , experiments have been unsuccessful). Then the continuation value of firm  $i$  (from time  $t_0$  onwards) when it chooses to experiment with probability 1 at time  $t_0 + t$  is

$$(10) \quad v_n(t) = \int_{t_0}^{t_0+t} \lambda_n(n-1) e^{-\lambda_n(n-1)(z-t_0)} e^{-r(z-t_0)} [p\Pi_2 + (1-p)v_{n-1}] dz \\ + e^{-\lambda_n(n-1)t} e^{-rt} p\Pi_2,$$

where  $v_{n-1}$  is the maximum value that the firm can obtain when there are  $n - 1$  firms that have not yet experimented (where we again use  $v$  since this expression refers to the continuation value from time  $t_0$  onwards). Intuitively,  $\lambda_n(n - 1) \times e^{-\lambda_n(n-1)(z-t_0)}$  is the density at which one of the  $n - 1$  other firms mixing at the rate  $\lambda_n$  will experiment at time  $z \in (t_0, t_0 + t)$ . When this happens, it is successful with probability  $p$  and will be copied by all other firms, and each will receive a value of  $e^{-r(z-t_0)}\Pi_2$  (discounted back to  $t_0$ ). If it is unsuccessful (probability  $1 - p$ ), the number of remaining firms is  $n - 1$ , and this gives a value of  $v_{n-1}$ . If no firm experiments until time  $t$ , firm  $i$  chooses to experiment at this point and receives  $e^{-rt}p\Pi_2$ . The probability of this event is  $1 - \int_{t_0}^{t_0+t} \lambda_n(n-1) e^{-\lambda_n(n-1)(z-t_0)} dz = e^{-\lambda_n(n-1)t}$ . As usual, in a mixed-strategy equilibrium,  $v_n(t)$  needs to be independent of  $t$  and moreover, it is clearly differentiable in  $t$ . So its derivative must be equal to zero. This implies

$$(11) \quad \lambda_n(n-1)[p\Pi_2 + (1-p)v_{n-1}] = (\lambda_n(n-1) + r)p\Pi_2.$$

Proposition 4 implies that there has to be mixing in all histories, thus

$$(12) \quad v_n = p\Pi_2 \text{ for all } n \geq 2.$$

Intuitively, mixing implies that the firm is indifferent between experimentation and waiting, and thus its continuation payoff must be the same as the payoff from experimenting immediately, which is  $p\Pi_2$ . Combining (11) and (12) yields

$$(13) \quad \lambda_n = \frac{r\Pi_2}{(1-p)(n-1)\Pi_1}.$$

This derivation implies that in the economy with  $N$  firms, each firm starts mixing at the flow rate  $\lambda_N$ . Following an unsuccessful experimentation, they increase their flow rate of experimentation to  $\lambda_{N-1}$ , and so on.

The derivation leading up to (13) easily generalizes when we relax (9). To demonstrate this, let us relax (9) and instead strengthen Assumption 1 to:

ASSUMPTION 2:

$$\Pi_n > p\Pi_1 \text{ for all } n.$$

The value of experimenting at time  $t$  (starting with  $n$  firms) is now given by a generalization of (10):

$$\begin{aligned} v_n(t) = & \int_{t_0}^{t_0+t} \lambda_n(n-1)e^{-\lambda_n(n-1)(z-t_0)}e^{-r(z-t_0)}[p\Pi_n + (1-p)v_{n-1}]dz \\ & + e^{-\lambda_n(n-1)t}e^{-rt}p\Pi_n. \end{aligned}$$

Again, differentiating this expression with respect to  $t$  and setting the derivative equal to zero gives the equivalent indifference condition to (11) as

$$(14) \quad \lambda_n(n-1)[p\Pi_n + (1-p)v_{n-1}] = (\lambda_n(n-1) + r)p\Pi_n.$$

for  $n = 2, \dots, N$ . In addition, we still have

$$v_n = p\Pi_n \text{ for all } n \geq 2.$$

Combining this with (14), we obtain

$$(15) \quad (n-1)\lambda_n = \frac{r}{1-p} \cdot \frac{\Pi_n}{\Pi_{n-1}} \text{ for } n = 2, \dots, N,$$

and let us adopt the convention that  $\lambda_1 = +\infty$ . Note that the expression on the left-hand side is the aggregate rate of experimentation that a firm is facing from the remaining firms.

This derivation establishes the following proposition.

**PROPOSITION 5:** *Suppose that Assumption 2 holds. Then there exists a unique symmetric equilibrium. In this equilibrium, when there are  $n = 1, 2, \dots, N$  firms that have not yet experimented, each experiments at the constant flow rate  $\lambda_n$  as given by (15). A successful innovation is immediately copied by all remaining firms. An unsuccessful experimentation starting with  $n \geq 3$  firms is followed by all remaining firms experimenting at the flow rate  $\lambda_{n-1}$ .*

An interesting feature of Proposition 5 is that after an unsuccessful experimentation, the probability of further experimentation may decline. Whether this is the case or not depends on how fast  $\Pi_n$  decreases in  $n$ .

### III. Patents and Optimal Allocations

The analysis so far has established that symmetric equilibria involve mixed strategies, potential delays, and also staggered experimentation (meaning that with probability 1, one of the firms will experiment before others). Asymmetric equilibria avoid delays, but also feature staggered experimentation. Moreover, they are less natural, because they involve one of the firms never acting (experimenting) until the other one does, and also because they give potentially very different payoffs to different firms. In this section, we first establish the inefficiency of (symmetric) equilibria. We then suggest that an appropriately designed patent system can implement optimal allocations. While all of the results in the section hold for  $N \geq 2$  firms, we focus on the case with two firms to simplify notation.

#### A. Welfare

It is straightforward to see that symmetric equilibria are Pareto suboptimal. Suppose that there exists a social planner that can decide the experimentation time for each firm. Suppose first that the social planner would like to maximize the sum of the present discounted values of the two firms (firm profits). Clearly, in practice an optimal allocation (and thus the objective function of the social planner) should also incorporate the implications of innovations on consumers. We discuss this issue next and show that it does not affect our qualitative conclusions.

The social planner could adopt one of two strategies:

- 1) *Staggered experimentation*: this would involve having one of the firms experiment at  $t = 0$ ; if it is successful, then the other firm would copy the innovation, and otherwise the other firm would experiment immediately. Denote the surplus generated by this strategy by  $S_1^P$ .
- 2) *Simultaneous experimentation*: this would involve having both firms experiment immediately at  $t = 0$ . Denote the surplus generated by this strategy by  $S_2^P$ .

When we focus on the present discounted value of firm profits,  $S_1^P$  and  $S_2^P$  have simple expressions. In particular,

$$(16) \quad S_1^P = 2p\Pi_2 + (1 - p)p\Pi_1.$$

Intuitively, one of the firms experiments first and is successful with probability  $p$ . When this happens, the other firm copies a successful innovation, with total payoff  $2\Pi_2$ . With the complementary probability,  $1 - p$ , the first firm is unsuccessful, and

the second firm experiments independently, with expected payoff  $p\Pi_1$ . These payoffs occur immediately after the first experimentation and thus are not discounted.

The other strategy is to have both firms experiment immediately, which generates expected surplus

$$(17) \quad S_2^P = 2p\Pi_1.$$

The comparison of  $S_1^P$  and  $S_2^P$  implies that simultaneous experimentation by both firms is optimal when  $2\beta < 1 + p$ . In contrast, when  $2\beta > 1 + p$ , the optimal allocation involves one of the firms experimenting first, and the second firm copying successful innovations.

The alternative is to incorporate consumer surplus (welfare) as well as producer surplus (profits) into the comparison of staggered and simultaneous experimentation. We have so far not modeled the demand for new products or specified the details of product market competition between firms, so different relative benefits to consumers from independent innovations and from copying are consistent with our approach. In particular, we can denote consumer surplus from a new innovation by  $C_1$  (and implicitly assume that consumer surplus from two independent innovations is  $2C_1$ ) and from two firms implementing the same project by  $2C_2$ . The relative magnitudes of  $C_1$  and  $C_2$  will be determined by consumer preferences and market structure. For example, each innovation may correspond to a new product and two firms implementing the same project may imply they both supply the same product and engage in product market competition (for example, à la Cournot). Then the magnitude of  $C_2$  relative to  $C_1$  will be determined by how much duopoly prices are lower than the monopoly price. If the two firms produce differentiated varieties, even when they implement the same innovation, then the magnitude of  $C_2$  will depend on consumers' love for variety. In any case, we can write the social surplus from staggered and simultaneous experimentation after incorporating the consumer surplus as

$$S_1^P = 2p(\Pi_2 + C_2) + (1 - p)p(\Pi_1 + C_1)$$

$$S_2^P = 2p(\Pi_1 + C_1).$$

Denoting  $\gamma \equiv (\Pi_2 + C_2)/(\Pi_1 + C_1)$ , it is then clear that simultaneous experimentation is optimal according to this extended notion of social surplus when  $2\gamma < 1 + p$ , and staggered experimentation and copying is optimal when  $2\gamma > 1 + p$ .

The discussion above is summarized in the next proposition (proof in the text).

**PROPOSITION 6:** *First focus on social surplus incorporating only firm profits and suppose that*

$$(18) \quad 2\beta > 1 + p,$$

*then the optimal allocation involves staggered experimentation, that is, experimentation by one firm and copying of successful innovations. If (18) does not hold, then*



the optimal allocation for the firms involves immediate experimentation by both firms. When  $2\beta = 1 + p$ , both staggered experimentation and immediate experimentation are socially optimal.

Next focus on social surplus incorporating firm profits and consumer surplus. Then, when  $2\gamma > 1 + p$ , the optimal allocation involves staggered experimentation, when  $2\gamma < 1 + p$ , the optimal allocation involves simultaneous extermination, and when  $2\gamma = 1 + p$ , both staggered and simultaneous extermination are optimal.

It is then straightforward to compare optimal and equilibrium allocations. For brevity, let us focus on social surplus from the viewpoint of firms alone. The (unique) symmetric equilibrium generates surplus for the firms

$$(19) \quad S^E = \int_0^\infty 2\lambda^* e^{-(2\lambda^*+r)t} [2p\Pi_2 + (1-p)p\Pi_1] dt$$

$$= \frac{2\lambda^*}{2\lambda^* + r} [2p\Pi_2 + (1-p)p\Pi_1] = 2p\Pi_2,$$

where  $\lambda^*$  is the (constant) equilibrium flow rate of experimentation given by (5).<sup>8</sup> The first line of (19) applies because the time of first experimentation corresponds to the first realization of one of two random variables, both with an exponential distribution with parameter  $\lambda^*$  and time is discounted at the rate  $r$ . If the first experimentation is successful, which has probability  $p$ , surplus is equal to  $2\Pi_2$ , and otherwise (with probability  $1-p$ ), the second firm also experiments, with expected payoff  $p\Pi_1$ . The second line is obtained by solving the integral and substituting for (16). An alternative way to obtain that  $S^E = 2p\Pi_2$  is by noting that at equilibrium the two firms are mixing with a constant flow of experimentation for all times, thus the expected payoff for each should be equal to the payoff when they experiment at time  $t = 0$ , i.e.,  $p\Pi_2$ . If instead social surplus incorporates both firm profits and consumer welfare, we would have

$$S^E = 2p\Pi_2 \left( 1 + \frac{2C_2 + (1-p)C_1}{2\Pi_2 + (1-p)\Pi_1} \right).$$

A straightforward comparison shows that  $S^E$  is always (strictly) less than the higher of  $S_1^P$  and  $S_2^P$ . Therefore, the unique symmetric equilibrium is always inefficient. Moreover, this inefficiency can be quantified in a simple manner. Let  $S^P = \max\{S_1^P, S_2^P\}$  and consider the ratio of equilibrium social surplus to the social surplus in the optimal allocation as a measure of inefficiency:

$$S \equiv \frac{S^E}{S^P}.$$

<sup>8</sup>Instead, asymmetric equilibria are identical to the first strategy of the planner and thus generate surplus  $S_1^P$  (recall Section IB).

Naturally, the lower is  $\mathcal{S}$ , the more inefficient is the equilibrium.

Clearly,  $\mathcal{S} < 1$ , so that the equilibrium is always inefficient as stated above. More specifically, let us focus on social surplus incorporating only firm profits and suppose that (18) holds. Then, the source of inefficiency is delayed experimentation. In this case,

$$\begin{aligned}\mathcal{S} &= \frac{S^E}{S_1^P} \\ &= \frac{2\lambda^*}{2\lambda^* + r} = \frac{2\beta}{2\beta + 1 - p},\end{aligned}$$

where the last equality simply uses (5). It is clear that  $\mathcal{S}$  is minimized, for given  $p$ , as  $\beta = (1 + p)/2$  (its lower bound given (18)). In that case, we have

$$\mathcal{S} = \frac{1 + p}{2}.$$

In addition, as  $p \downarrow 0$ ,  $\mathcal{S}$  can be as low as  $1/2$ .

Next, consider the case where (18) does not hold. Then

$$\begin{aligned}\mathcal{S} &= \frac{S^E}{S_2^P} \\ &= \frac{2\lambda^*}{2\lambda^* + r} \frac{2p\Pi_2 + (1 - p)p\Pi_1}{2p\Pi_1} = \beta,\end{aligned}$$

where the last equality again uses (5) and the definition of  $\beta$  from (1). Since this expression applies when  $\beta < 1 + p$ ,  $\beta$  can be arbitrarily small as long as  $p$  is small (to satisfy the constraint that  $\beta > p$ ), and thus in this case  $\mathcal{S} \downarrow 0$ . In both cases, the source of inefficiency of the symmetric equilibrium is because it generates insufficient incentives for experimentation. In the first case, this exhibits itself as delayed experimentation, and in the second, as lack of experimentation by one of the firms.

This discussion establishes the following proposition (proof in the text).

**PROPOSITION 7:** *Focus on social surplus incorporating only firm profits.*

- 1) *Asymmetric equilibria are Pareto optimal and maximize social surplus when (18) holds, but fail to maximize social surplus when (18) does not hold.*
- 2) *The unique symmetric equilibrium is always Pareto suboptimal and never maximizes social surplus. When (18) holds, this equilibrium involves delayed experimentation, and when (18) does not hold, there is insufficient experimentation.*
- 3) *When (18) holds, the relative surplus in the equilibrium compared to the surplus in the optimal allocation,  $\mathcal{S}$ , can be as small as  $1/2$ . When (18) does not*

*hold, the symmetric equilibrium can be arbitrarily inefficient. In particular,  $S \downarrow 0$  as  $p \downarrow 0$  and  $\beta \downarrow 0$ .*

It is straightforward to verify that, when focusing on social surplus incorporating both consumer surplus and firm profits, the results in this proposition apply exactly if consumer surplus is proportional to firm profits, i.e.,  $C_2 = \kappa\Pi_2$  and  $C_1 = \kappa\Pi_1$ . If this is not the case, then part 1 still applies, and, in addition, the worst-case scenario considered in part 3 can become even worse because of the misalignment between firm profits and consumer surplus. Given the similarity of the insights in these two cases, in the remainder of the paper we focus on social surplus incorporating only firm profits.

### B. Patents

The previous subsection established the inefficiency of the symmetric equilibrium resulting from delayed and insufficient experimentation. In this subsection, we discuss how patents can solve or ameliorate this problem. Our main argument is that a patent system provides incentives for greater experimentation or for experimentation without delay.

We model a simple patent system, whereby a patent is granted to any firm that undertakes a successful innovation. If a firm copies a patented innovation, it has to make a payment (compulsory license fee)  $\eta$  to the holder of the patent. We discuss the relationship between this payment and licensing fees in the next subsection. An appropriately designed patent system (i.e., the appropriate level of  $\eta$ ) can achieve two objectives simultaneously. First, it can allow firms to copy others when it is socially beneficial for the knowledge created by innovations to spread to others (and prevent it when it is not beneficial). Second, it can provide compensation to innovators, so that incentives to free-ride on others are weakened. In particular, when staggered experimentation is optimal, a patent system can simultaneously provide incentives to one firm to innovate early, and to the other firm to copy an existing innovation. When  $\eta$  is chosen appropriately, the patent system provides incentives for the ex post transfer of knowledge. However, more crucially, it also encourages innovation because an innovation that is copied becomes more profitable than copying another innovation and paying the patent fee. The key here is that the incentives provided by the patent system are “conditional” on whether the other firm has experimented or not, and thus induce an “asymmetric” response from the two firms. This makes innovation relatively more profitable when the other firm copies and less profitable when the other firm innovates. This incentive structure encourages one of the firms to be the innovator precisely when the other firm is copying. Consequently, the resulting equilibria resemble asymmetric equilibria. Moreover, these asymmetric incentives imply that, when the patent system is designed appropriately, a symmetric equilibrium no longer exists. It is less profitable for a firm to innovate when the other firm is also innovating, because innovation no longer brings patent revenues. Conversely, it is not profitable for a firm to wait when the other firm waits, because there is no innovation to copy in that case.

Our main result in this subsection formalizes these ideas. We state this result in the following proposition and then provide most of the proof, which is intuitive, in the text.

**PROPOSITION 8:** *Consider the model with two firms. Suppose that Assumption 1 holds. Then:*

- 1) *When (18) holds, a patent system with*

$$\eta \in \left[ \frac{(1-p)\Pi_1}{2}, \Pi_2 - p\Pi_1 \right)$$

*(which is feasible in view of (18)), implements the optimal allocation, which involves staggered experimentation, in all equilibria. That is, in all equilibria one firm experiments first, and the other one copies a successful innovation and experiments immediately following an unsuccessful experimentation.*

- 2) *When (18) does not hold, then the optimal allocation, which involves simultaneous experimentation, is implemented as the unique equilibrium by a patent system with*

$$\eta > \Pi_2 - p\Pi_1.$$

*That is, there exists a unique equilibrium in which both firms immediately experiment.*

Let us start with the first claim in Proposition 8. We outline the argument for why  $\eta < \Pi_2 - p\Pi_1$  implies that there exists an equilibrium with staggered experimentation, and  $\eta \geq (1-p)\Pi_1/2$  ensures that other equilibria, which involve delayed experimentation, are ruled out. Observe that since  $\eta < \Pi_2 - p\Pi_1$ , the equilibrium involves copying of a successful innovation by a firm that has not acted yet. However, incentives for delaying to copy are weaker because copying now has an additional cost  $\eta$ , and innovation has an additional benefit  $\eta$  if the other firm is imitating. Suppose that firm  $\sim i$  will innovate at some date  $T > 0$  (provided that firm  $i$  has not done so until then). Then the payoffs to firm  $i$  when it chooses experimentation and waiting are

$$\text{experiment now} = p(\Pi_2 + \eta)$$

$$\text{wait} = e^{-rT}(p(\Pi_2 - \eta) + (1-p)p\Pi_1).$$

It is clear that for any  $T > 0$ , experimenting is a strict best response, since

$$p(\Pi_2 + \eta) \geq p(\Pi_2 - \eta) + (1-p)p\Pi_1,$$

given that  $\eta \geq (1-p)\Pi_1/2$ . So experimenting immediately against a firm that is waiting is optimal. To show that all equilibria implement the optimal allocation, we also need to show that both firms experimenting immediately is not an equilibrium. Suppose they did so. Then the payoff to each firm, as a function of whether they experiment or wait, would be

$$\text{experiment now} = p\Pi_1$$

$$\text{wait} = p(\Pi_2 - \eta) + (1 - p)p\Pi_1.$$

Waiting is a strict best response since

$$p(\Pi_2 - \eta) + (1 - p)p\Pi_1 > p\Pi_1,$$

which holds in view of the fact that  $\eta < \Pi_2 - p\Pi_1$ . This argument makes it intuitive that patents induce an equilibrium structure without delay: waiting is (strictly) optimal when the other firm is experimenting immediately and experimenting immediately is (strictly) optimal when the other firm is waiting. To establish this claim formally, we need to prove that there are no mixed strategy equilibria. This is done in the next lemma.

**LEMMA 2:** *When equation (18) holds, there does not exist any equilibrium with mixing.*

**PROOF:**

Let us write the expected present discounted value of experimenting at time  $t$  for firm  $i$  when firm  $\sim i$  experiments at the flow rate  $\lambda(t)$  as in (7) in the proof of Proposition 3, except that we now take patent payments into account and use equation (18) so that copying a successful innovation is still profitable. This expression is

$$\begin{aligned} V(t) &= \int_0^t \lambda(z) e^{-m(z)} e^{-rz} [p(\Pi_2 - \eta) + (1 - p)p\Pi_1] dz \\ &\quad + e^{-m(t)} e^{-rt} p(\Pi_2 + \eta), \end{aligned}$$

where  $m(t)$  is given by (6) in the proof of Proposition 3. This expression must be constant for all  $t$  in the support of the mixed-strategy equilibrium. The argument in the proof of Proposition 3 establishes that  $\lambda(t)$  must satisfy

$$\lambda(t)[p(\Pi_2 - \eta) + (1 - p)p\Pi_1] = (r + \lambda(t))p(\Pi_2 - \eta).$$

It can be verified easily that since  $\eta \geq (1 - p)\Pi_1/2$ , this equation cannot be satisfied for any  $\lambda(t) \in \mathbb{R}_+$  (for any  $t$ ). Therefore, there does not exist any equilibrium with mixing.

Let us next turn to the second claim in the proposition. Suppose that (18) is not satisfied and let  $\eta > \Pi_2 - p\Pi_1$ . Then it is not profitable for a firm to copy a successful innovation. Therefore, both firms have a unique optimal strategy which is to experiment immediately, which coincides with the optimal allocation characterized in Proposition 6.

The intuition for the results in Proposition 8 can also be obtained by noting that the patent system is inducing experimenters to internalize the externalities that they create. Let us focus on part 1 and suppose that firm 1 experiments while firm 2

delays and copies a successful innovation by firm 1. In this case, the social surplus is equal to  $2p\Pi_2 + (1 - p)p\Pi_1$ . Firm 1 only receives  $p\Pi_2$  without a patent, and if it were to deviate and delay experimentation, firm 2 would instead receive  $p\Pi_2$ . Thus to internalize the positive externality that it is creating, firm 1 needs to be compensated for  $(1 - p)p\Pi_1$ . A license fee of  $\eta \geq (1 - p)\Pi_1/2$  achieves this, since by experimenting, firm 1 receives this license fee with probability  $p$  and by delaying, it would have had to pay the same license fee with probability  $p$  (and thus  $2p\eta \geq (1 - p)p\Pi_1$ ). The requirement that  $\eta < \Pi_2 - p\Pi_1$  then simply ensures that firm 2 indeed wishes to copy a successful innovation despite the license fee.

The preceding discussion and Proposition 8 show how an appropriately designed patent system can be useful by providing stronger incentives for experimentation. When simultaneous experimentation by all parties is socially beneficial, a patent system can easily achieve this by making copying (or “free-riding”) unprofitable. On the other hand, when ex post transfer of knowledge is socially beneficial, the patent system can instead ensure this while also preventing delays in all equilibria. It is important to emphasize that, in the latter case, the patent system provides such incentives *selectively*, so that only one of the firms engages in experimentation and the other firm potentially benefits from the innovation of the first firm. In contrast to patents, simple subsidies to research could not achieve this objective. This is stated in the next proposition and highlights the particular utility of a patent system in this environment.

**PROPOSITION 9:** *Suppose that equation (18) holds. Consider a direct subsidy  $w > 0$  given to a firm that experiments. There exists no  $w \geq 0$  such that all equilibria with subsidies correspond to the optimal allocation.*

**PROOF:**

This is straightforward to see. If  $w \geq \Pi_2 - p\Pi_1$ , there exists an equilibrium in which both firms experiment immediately and if  $w < \Pi_2 - p\Pi_1$ , the symmetric mixed-strategy equilibrium with delayed experimentation survives.

It is also clear that the same argument applies to subsidies to successful innovation or any combination of subsidies to innovation and experimentation.

### *C. Patents and License Fees*

The analysis in the previous subsection assumed that a firm can copy a successful innovation and in return it has to make some pre-specified payment (compulsory license fee)  $\eta$  to the original innovator. In practice, patents often provide exclusive rights to the innovator, who is then allowed to license its product or discovery to other firms. If so, the license fee  $\eta$  would need to be negotiated between the innovator and the (potential) copying firm rather than determined in advance. While such voluntary licensing is an important aspect of the patent system in practice, it is not essential for the theoretical insights we would like to emphasize.

To illustrate this, let us suppose that the copying firm is developing a different but highly substitutable product to the first innovation. Suppose further that the patent system gives exclusive rights to the innovator, but if the second firm copies



a successful innovation, the court system needs to determine damages. How the court system functions is also part of the patent system. In particular, suppose that if a firm copies a successful innovation without licensing, and the innovator brings a lawsuit, it will succeed with probability  $\rho \in (0, 1)$  and the innovator will receive damages equal to  $\kappa(\Pi_1 - \Pi_2)$ , where  $\kappa > 0$ . We ignore legal fees. Given this legal environment, let us interpret  $\eta$  as a license fee negotiated between the potential copying firm and the innovator. For simplicity, suppose that this negotiation can be represented by a take-it-or-leave-it offer by the innovator (this has no effect on the conclusions of this subsection). If the two firms agree to licensing, their joint surplus is  $2\Pi_2$ . If they disagree, then the outside option of the copying firm is  $\max\{p\Pi_1; \Pi_2 - \rho\kappa(\Pi_1 - \Pi_2)\}$ , where the max operator takes care of the fact that the best alternative for the “copying” firm may be to experiment if there is no explicit licensing agreement. Without licensing, the innovator will receive an expected return of  $\Pi_2 + \rho\kappa(\Pi_1 - \Pi_2)$  if  $\Pi_2 - \rho\kappa(\Pi_1 - \Pi_2) \geq p\Pi_1$  and  $\Pi_1$  otherwise. This implies that the negotiated license fee, as a function of the parameters of the legal system, will be

$$\eta(\rho, \kappa) = \begin{cases} \rho\kappa(\Pi_1 - \Pi_2) & \text{if } p\Pi_1 < \Pi_2 - \rho\kappa(\Pi_1 - \Pi_2), \\ \Pi_2 - p\Pi_1 & \text{if } p\Pi_1 \geq \Pi_2 - \rho\kappa(\Pi_1 - \Pi_2) \text{ and } 2\Pi_2 > \Pi_1, \\ \infty & \text{otherwise,} \end{cases}$$

where  $\infty$  denotes a prohibitively expensive license fee, such that no copying takes place. Clearly, by choosing  $\rho$  and  $\kappa$ , it can be ensured that  $\eta(\rho, \kappa)$  is greater than  $\Pi_2 - p\Pi_1$  when (18) does not hold and is between  $(1 - p)\Pi_1/2$  and  $\Pi_2 - p\Pi_1$  when it holds. This illustrates how an appropriately designed legal enforcement system can ensure that equilibrium license fees play exactly the same role as the pre-specified patent fees did in Proposition 8.

#### IV. Model with Heterogeneous Information

Throughout the remainder of the paper, we relax the assumption that all firms receive signals with identical precision. Instead, now signal quality differs across firms. We continue to assume that each firm receives a positive signal about a single project. But, the information content of these signals differs. We parameterize signal quality by the probability with which the indicated project is successful and denote it by  $p$  (or by  $p_i$  for firm  $i$ ). We distinguish two cases. First, we discuss the case when signals are publicly observed (we limit the discussion to two firms) and, then, we study the case when the signals are drawn from a known distribution represented by the cumulative distribution function  $G(p)$  ( $G$  is assumed to have strictly positive and continuous density  $g(p)$  over its support  $[a, b] \subset [0, 1]$ ) and the realization of  $p$  for each firm is independent of the realizations for others and is *private information*. For the case of private signals we discuss the case of two firms in the main text and relegate a discussion on the extension to multiple firms to Appendix B. Finally, throughout we focus on the equivalent of *symmetric equilibria*, where strategies do not depend on firm identity.

### A. Publicly Observed Signals

Let  $p_1, p_2$  denote the signals of firms 1 and 2, respectively. We also impose:

ASSUMPTION 3:

$$\pi_1 > \pi_2 > \min\{p_1, p_2\}\pi_1.$$

Note that Assumption 3 implies that firm  $i = \arg \min\{p_1, p_2\}$  would find it optimal to copy firm  $\sim i$ , if the latter was successful at experimentation. Also, note that when  $\min\{p_1, p_2\}\pi_1 \geq \pi_2$  the structure of the equilibrium is straightforward. Let us consider the following two cases: (1)  $\max\{p_1, p_2\}\pi_1 \geq \pi_2$  and (2)  $\max\{p_1, p_2\}\pi_1 < \pi_2$ . The next proposition characterizes the unique equilibrium (in fully mixed strategies prior to any experimentation) in both cases (the proof is omitted as it uses similar arguments to that of Proposition 3). For the remainder of the section, let  $p_{\max} \equiv \max\{p_1, p_2\}$ ,  $p_{\min} \equiv \min\{p_1, p_2\}$  and similarly  $i_{\max} \equiv \arg \max\{p_1, p_2\}$  and  $i_{\min} \equiv \arg \min\{p_1, p_2\}$ .

PROPOSITION 10: *Suppose that Assumption 3 holds and signals are publicly observed. Then, there exists a unique equilibrium in fully mixed strategies prior to any experimentation. In particular:*

- 1) Suppose  $p_{\max}\pi_1 < \pi_2$ . Then, in the unique fully mixed equilibrium, firm 1 uses the constant flow rate of experimentation  $\lambda_1 = rp_2\beta/(1-p_1)p_2 + (p_1-p_2)\beta$  and firm 2 uses the rate  $\lambda_2 = rp_1\beta/(1-p_2)p_1 + (p_2-p_1)\beta$ . Firm  $i$  immediately copies a successful innovation by firm  $\sim i$  and experiments if  $\sim i$  experiments unsuccessfully.
- 2) Suppose  $\max\{p_1, p_2\}\pi_1 \geq \pi_2$ . Then, in the unique fully mixed equilibrium, firm  $i_{\min}$  uses the constant flow rate of experimentation  $\lambda_{\min} = r\beta/1 - \beta$  and firm  $i_{\max}$  uses the rate  $\lambda_{\max} = rp_{\min}/(\beta - p_{\min})p_{\max}$ . Firm  $i_{\min}$  immediately copies a successful innovation by firm  $i_{\max}$  and experiments if  $i_{\max}$  experiments unsuccessfully. On the other hand, if  $i_{\min}$  experiments first, then  $i_{\max}$  experiments with its own research project (does not copy the potential innovation).

It is worth noting that when  $\max\{p_1, p_2\}\pi_1 \geq \pi_2$ , firm  $i_{\max}$  delays experimentation not to copy a potential innovation by firm  $i_{\min}$  but so as not to get copied by  $i_{\min}$ . Proposition 11 is analogous to Proposition 6 and describes the optimal allocation in this setting (proof is omitted).

PROPOSITION 11: *Suppose that signals are publicly observed and*

$$(20) \quad 2\beta \geq 1 + p_{\min},$$

*then the optimal allocation involves staggered experimentation, that is, experimentation by firm  $i_{\max}$  first and copying of successful innovations. If (20) does not hold,*

then the optimal allocation involves immediate experimentation by both firms. When  $2\beta = 1 + p_{\min}$ , both staggered experimentation and immediate experimentation are socially optimal.

Moreover, we can show that a patent system with:

$$\eta \in \left[ \min \left\{ \Pi_2 - p_{\max} \Pi_1, \frac{(1 - p_{\min})p_{\max} \Pi_1 - (p_{\max} - p_{\min})\Pi_2}{p_1 + p_2} \right\}, \Pi_2 - p_{\min} \Pi_1 \right)$$

implements the optimal allocation in all equilibria, when (20) holds. When (20) does not hold, then the optimal allocation is implemented as the unique equilibrium by a patent system with  $\eta > \Pi_2 - p_{\min} \Pi_1$  (the claim follows by similar arguments to those in Proposition 8). An interesting feature of the optimal allocation, illustrated by Proposition 11, is that it involves a *monotonicity*, whereby the firm with the strongest signal experiments earlier (no later) than the firm with the weaker signal. Yet, this monotonicity does not necessarily hold at equilibrium, since there is a positive probability that the firm with the weaker signal ( $i_{\min}$ ) experiments before the firm with the stronger signal ( $i_{\max}$ ).

### B. Private Signals

Throughout the remainder of the paper, we assume that  $p$ 's are drawn independently from a known distribution with cumulative distribution function  $G(p)$  and continuous density  $g(p)$  over its support. As the title of the subsection indicates, the realization of  $p$ 's are private information. We start with the following lemma, which follows from the definition of  $\beta$  in (1). It will play an important role in the analysis that follows (proof omitted).

**LEMMA 3:** *Suppose that signals are private information and that firm  $\sim i$  has innovated successfully. If  $p_i > \beta$ , firm  $i$  prefers to experiment with its own project. If  $p_i < \beta$ , firm  $i$  prefers to copy a successful project.*

Proposition 12 below provides a characterization of the unique symmetric equilibrium with two firms. We show that the equilibrium takes the following form: firms with strong signals (in particular,  $p \geq \beta$ ) experiment immediately, while those with weaker signals (i.e.,  $p < \beta$ ) experiment at time  $\tau(p)$  with  $\tau(\beta) = 0$ , unless there has been experimentation at any earlier time. Function  $\tau(p)$  is strictly decreasing and maps signals to time of experimentation provided that the other player has not yet experimented. The proof of the proposition uses a series of lemmas and is relegated to the Appendix.

**PROPOSITION 12:** *Suppose that signals are private information and let the support of  $G$  be  $[a, b] \subset [0, 1]$  and define  $\bar{b} \equiv \min\{\beta, b\}$  and*

$$(21) \bar{\tau}(p) \equiv \frac{1}{r\beta G(\bar{b})} \left[ \log G(\bar{b})(1 - \bar{b}) - \log G(p)(1 - p) + \int_p^{\bar{b}} \log G(z) dz \right].$$

Then the unique symmetric equilibrium involves:

$$\tau(p) = \begin{cases} 0 & \text{if } p \geq \beta \\ \bar{\tau}(p) & \text{if } p \in [a, \beta). \end{cases}$$

That is, firms with  $p \geq \beta$  experiment immediately and firms with  $p \in [a, \beta)$  experiment at time  $\bar{\tau}(p)$  unless there has been an experimentation at  $t < \bar{\tau}(p)$ . If there is experimentation at  $t < \bar{\tau}(p)$ , then a firm with  $p \in [a, \beta)$  copies it if the previous attempt was successful and experiments immediately if it was unsuccessful.

A particularly simple example to illustrate Proposition 12 is obtained when  $G$  is uniform over  $[a, b]$  for  $0 < a < b \leq \beta$ . In that case,

$$(22) \quad \tau(p) = \frac{1}{r\beta} [p - \log p - b + \log b] \text{ for all } p \in [a, b].$$

An interesting feature of the symmetric equilibria in this case is evident from (22): for  $a$  arbitrarily close to 0, experimentation may be delayed for arbitrarily long time. It can be verified from (21) that this is a general feature (for types arbitrarily close to the lower support  $a$ ,  $-\log G(p)$  is arbitrarily large).

### C. Welfare

In this subsection, we discuss welfare in the environment with private, heterogeneous signals studied in the previous subsection. In particular, consider a social planner that is interested in maximizing social surplus (but focusing only on firm profits, recall Section III). What the social planner can achieve will depend on her information and on the set of instruments that she has access to. For example, if the social planner observes the signal quality,  $p$ , for each firm, then she can achieve a much better allocation than the equilibrium characterized above. However, it is more plausible to limit the social planner to the same information structure. In that case, the social planner will have to choose either the same equilibrium allocation as in the symmetric equilibria characterized in the previous two sections, or she will implement an asymmetric equilibrium, where one of the firms is instructed to experiment first regardless of its  $p$  (this cannot be conditioned on  $p$  since  $p$  is private information).<sup>9</sup>

More specifically, let us focus on the economy with two firms and suppose that the support of  $G$  is  $[a, b] \subset [0, \beta]$ . In this case, without eliciting information about the realization of firm types, the  $p$ 's, the planner has three strategies:

- 1) *Staggered asymmetric experimentation*: in this case, the social planner would instruct one of the firms to experiment immediately and then have the other

<sup>9</sup>Yet another alternative is to specify exactly the instruments available to the planner and characterize the solution to a mechanism design problem by the planner. However, if these instruments allow messages and include payments conditional on messages, the planner can easily elicit the necessary information from the firms.

firm copy if there is a successful innovation. Since the social planner does not know the  $p$ 's, she has to pick the experimenting firm randomly. We denote the social surplus generated by this strategy by  $S_1^P$ .

- 2) *Staggered equilibrium experimentation*: alternatively, the social planner could let the firms play the symmetric equilibrium of the previous two sections, whereby a firm of type  $p$  will experiment at time  $\tau(p)$  unless there has previously been an experimentation by the other firm. We denote the social surplus generated by this strategy by  $S^E$ , since this is the same as the equilibrium outcome.<sup>10</sup>
- 3) *Simultaneous experimentation*: in this case, the social planner would instruct both firms to experiment immediately. We denote the social surplus generated by this strategy by  $S_2^P$ .

The social surpluses from these different strategies are given as follows. In the case of staggered asymmetric experimentation, we have

$$S_1^P = \int_a^b \left[ p_1 2\Pi_2 + (1 - p_1) \left( \int_a^b p_2 dG(p_2) \right) \Pi_1 \right] dG(p_1).$$

In contrast, the expected surplus from the unique (mixed-strategy) symmetric equilibrium can be written as

$$S^E = \int_a^b e^{-r\tau(\max\{p_1, p_2\})} \left[ \max\{p_1, p_2\} 2\Pi_2 + (1 - \max\{p_1, p_2\}) \int_a^b \min\{p_1, p_2\} \Pi_1 \right] dG(p_1) dG(p_2).$$

Intuitively, this expression follows by observing that in the equilibrium as specified in Proposition 15, the firm with the stronger signal (higher  $p$ ) will experiment first, so there will be delay until  $\max\{p_1, p_2\}$ . At that point, this firm will succeed with probability  $\max\{p_1, p_2\}$ , in which case the second firm will copy. If the first firm fails (probability  $1 - \max\{p_1, p_2\}$ ), then the second firm experiments and succeeds with probability  $\min\{p_1, p_2\}$ . Since both  $p_1$  and  $p_2$  are randomly drawn independently from  $G$ , we integrate over  $G$  twice to find the expected surplus.

The surplus from simultaneous experimentation, on the other hand, takes a simple form and is given by

$$S_2^P = 2\Pi_1 \int_a^b p dG(p),$$

<sup>10</sup>Without eliciting information about firm types and without using additional instruments, the social planner cannot implement another monotone staggered experimentation allocation. For example, she could announce that if there is no innovation until some time  $t > 0$ , one of the firms will be randomly forced to experiment. But such schemes will not preserve monotonicity, since at time  $t$ , it may be the firm with lower  $p$  that may be picked for experimentation. In the next subsection, we discuss how she can implement better allocations using patent payments.

since in this case each firm is successful and generates payoff  $\Pi_1$  with probability  $p$  distributed with distribution function  $G$ .

In this case, there is no longer any guarantee that  $\max\{S_1^p, S_2^p\} > S^E$ . Therefore, the symmetric equilibrium may generate a higher expected surplus (relative to allocations in which the social planner does not have additional instruments). To illustrate this, let us consider a specific example, where  $p$  has a uniform distribution over  $[0, \beta]$ . In this case, staggered asymmetric experimentation gives

$$S_1^p = \int_0^\beta \int_0^\beta 2p_1\Pi_2 + (1 - p_1)p_2\Pi_1 dp_2 dp_1 = \Pi_2 \left( \frac{1}{2} + \frac{3}{4}\beta \right),$$

whereas simultaneous experimentation gives

$$S_2^p = \int_0^\beta 2p\Pi_1 dp = \beta\Pi_1 = \Pi_2.$$

Comparing simultaneous experimentation and staggered asymmetric experimentation, we can conclude that  $S_1^p > S_2^p$  whenever  $\beta > 2/3$  and  $S_1^p < S_2^p$  whenever  $\beta < 2/3$ , showing that, as in the case with common signals, either simultaneous or staggered experimentation might be optimal. Next, we can also compare these surpluses to  $S^E$ . Since  $p$  is uniformly distributed in  $[0, \beta]$ , (25) implies that

$$\tau(p) = \frac{1}{r\beta} [p - \log p - \beta + \log \beta].$$

As a consequence,  $\max\{p_1, p_2\}$  has a Beta (2, 1) distribution (over  $[0, \beta]$ ) while  $\min\{p_1, p_2\}$  is distributed Beta (1, 2). Then evaluating the expression for  $S^E$ , we find that when  $0 \leq \beta \leq 2/3$ ,  $S_2^p > S^E$ , so simultaneous experimentation gives the highest social surplus. When  $2/3 \leq \beta \leq \beta^* \simeq 0.895$ ,  $S_1^p > S^E$ , so that staggered asymmetric experimentation gives the highest social surplus. Finally, when  $\beta^* \leq \beta \leq 1$ ,  $S^E > S_1^p > S_2^p$ , so the symmetric equilibrium gives higher social surplus than both staggered asymmetric experimentation and simultaneous experimentation.

Finally, it is also straightforward to see that by choosing  $G$  to be highly concentrated around a particular value  $\bar{p}$ , we can repeat the same argument as in Section IIIA and show that the symmetric equilibrium can be arbitrarily inefficient relative to the optimal allocation.

#### D. Equilibrium with Patents

Equilibria with patents are also richer in the presence of heterogeneity. Let us again focus on the case in which there are two firms. Suppose that there is a patent system identical to the one discussed in Section IIIB, whereby a firm that copies a successful innovation pays  $\eta$  to the innovator. Let us define

$$(23) \quad p^\eta \equiv \frac{\Pi_2 - \eta}{\Pi_1}.$$



It is clear, with a reasoning similar to Lemma 3, that only firms with  $p < p^\eta$  will copy when the patent system specifies a payment of  $\eta$ . The next proposition characterizes the structure of equilibria with patents (the proof is relegated to the Appendix).

**PROPOSITION 13:** *Suppose that there are two firms and the patent system specifies a payment  $\eta > 0$  for copying. Let  $p^\eta$  be given by (23), the support of  $G$  be  $[a, b] \subset [0, 1]$ , and define  $\bar{b} \equiv \min\{b, p^\eta\}$  and*

$$(24) \quad \bar{\tau}^\eta(p) \equiv \frac{1}{r(\Pi_2 + \eta)G(\bar{b})} \left[ \log G(\bar{b})(\Pi_1 - 2\eta - \bar{b}\Pi_1) - \log G(p) \right. \\ \left. \times (\Pi_1 - 2\eta - p\Pi_1) + \Pi_1 \int_p^{\bar{b}} \log G(z) dz \right].$$

Then the unique symmetric equilibrium involves:

$$\tau^\eta(p) = \begin{cases} 0 & \text{if } p \geq p^\eta \\ \bar{\tau}^\eta(p) & \text{if } p \in [a, p^\eta]. \end{cases}$$

That is, firms with  $p \geq p^\eta$  experiment immediately and firms with  $p \in [a, p^\eta]$  experiment at time  $\bar{\tau}^\eta(p)$  unless there has been an experimentation at  $t < \bar{\tau}^\eta(p)$ .

Moreover, a higher  $\eta$  tends to reduce delay. In particular:

- for any  $\eta' > \eta$  such that  $b < p^\eta$  and  $b < p^{\eta'}$ , we have  $\tau^{\eta'}(p) \leq \tau^\eta(p)$  for all  $p \in [a, b]$ , with strict inequality whenever  $\tau^\eta(p) > 0$ ;
- for any  $\eta'$  such that  $b > p^{\eta'}$ , there exists  $p^*(\eta') \in [0, p^{\eta'})$  such that  $\tau^\eta(p)$  is decreasing in  $\eta$  starting at  $\eta = \eta'$  for all  $p \in [p^*(\eta'), p^{\eta']$ , with strict inequality whenever  $\tau^{\eta'}(p) > 0$ .

Note that the first bullet point considers the case when all firms would prefer to copy a successful innovation than to experiment on their own (since  $b < p^{\eta'} < p^\eta$ ), whereas the second bullet point considers the case when there is a positive probability that a firm obtains a strong enough signal and prefers to experiment on its own.

The result highlights an important role of patents in experimentation. When  $\eta$  increases,  $\tau(p)$  tends to become “steeper” so that there is less delay and thus “time runs faster.” In particular, whenever  $p^\eta < b$ ,  $\tau(p)$  is reduced by an increase in patent payments. When  $p^\eta > b$ , this does not necessarily apply for very low  $p$ 's, but is still true for high  $p$ 's. Overall, this result implies that as in the case with common  $p$ 's, patents tend to increase experimentation incentives and reduce delay. In the limit, when  $\eta$  becomes arbitrarily large, the equilibrium involves simultaneous experimentation. Nevertheless, as discussed in Section IVC, simultaneous experimentation may not be optimal in this case.

Alternatively (and differently from Proposition 13), a patent system can also be chosen such that the socially beneficial ex post transfer of knowledge takes place. In particular, suppose that there has been an innovation and the second firm has

probability of success equal to  $p$ . In this case, social surplus is equal to  $2\Pi_2$  if there is copying, and it is equal to  $\Pi_1 + p\Pi_1$  if the second firm is forced to experiment. This implies that to maximize ex post social welfare, firms with  $p \leq 2\beta - 1$  should be allowed to copy, whereas firms with  $p > 2\beta - 1$  should be induced to experiment. Clearly, from (23) choosing  $\eta = \Pi_1 - \Pi_2$  achieves this. Naturally, from Proposition 13, this will typically lead to an equilibrium with staggered experimentation. This argument establishes the following proposition (proof in the text).

**PROPOSITION 14:** *A patent system with  $\eta = \Pi_1 - \Pi_2$  induces the socially efficient copying and experimentation behavior for all  $p \in [a, b]$ , but typically induces delayed experimentation.*

The juxtaposition of Propositions 13 and 14 implies that when signal quality is heterogeneous and private information, the patent system can ensure either rapid experimentation or the socially beneficial ex post transfer of knowledge (and experimentation by the right types), but will not typically be able to achieve both objectives simultaneously. However, appropriately designed patents typically improve efficiency, as is stated in the following corollary. Moreover, note that unless the types distribution, i.e.,  $G$ , is skewed towards low signals, the optimal patent payment will satisfy  $\eta^* \geq \Pi_1 - \Pi_2$ .

**COROLLARY 1:** *Suppose that there are two firms and the patent system specifies a payment  $\eta > 0$  for copying. Then, the aggregate payoff of the firms is higher than the case when  $\eta = 0$ , unless both firms have very weak signals, i.e.,  $p_1, p_2 \leq p^*(\eta)$ , where  $p^*(\eta) < p^n$  is a constant.*

## V. Conclusion

This paper studied a simple model of experimentation and innovation. Each firm receives a private signal on the success probability of one of many potential research projects and decides when and which project to implement. A successful innovation can be copied by other firms. We show that symmetric equilibria, where actions do not depend on the identity of the firm, necessarily involve delayed and staggered experimentation. When the signal quality is the same for all players, the equilibrium is in mixed strategies (pure-strategy symmetric equilibria do not exist). When signal quality differs across firms, the equilibrium is represented by a function  $\tau(p)$  which specifies the time at which a firm with signal quality  $p$  experiments. As in the environment with common signal quality, the equilibrium may involve arbitrarily long delays.

We also show that the social cost of insufficient experimentation incentives can be arbitrarily large. The optimal allocation may require simultaneous rather than staggered experimentation. In this case, the efficiency gap between the optimal allocation and the equilibrium can be arbitrarily large. Instead, when the optimal allocation also calls for staggered experimentation, the equilibrium is inefficient because of delays. We show that in this case, the ratio of social surplus in the equilibrium to that in the optimal allocation can be as low as  $1/2$ .

One of the main arguments of the paper is that appropriately designed patent systems encourage experimentation and reduce delays without preventing efficient ex post transfer of knowledge across firms. Consequently, when signal quality is the same for all firms, an appropriately designed patent system can ensure that the optimal allocation results in all equilibria. Patents are particularly well-suited to providing the correct incentives when the optimal allocation also requires staggered experimentation. In this case, patents can simultaneously encourage one of the firms to play the role of a leader in experimentation, while providing incentives to others to copy successful innovations. Technically, appropriately designed patents destroy symmetric equilibria, which are the natural equilibria in the absence of patents but may involve a high degree of inefficiency. That patents are an attractive instrument in this environment can also be seen from our result that, while patents can implement the optimal allocation, there exists no simple subsidy (to experimentation, research, or innovation) that can achieve the same policy objective. When signal quality differs across firms, patents are again useful in encouraging experimentation and reduce delays, however, typically, they are unable to ensure the optimal allocation.

We believe that the role of patents in encouraging socially beneficial experimentation is more general than the simple model used in this paper. In particular, throughout the paper we only briefly considered the consumer side. It is possible that new innovations create benefits to consumers that are disproportionately greater than the use of existing successful innovations (as compared to the relative profitabilities of the same activities). In this case, the social benefits of experimentation are even greater and patents can also be useful in preventing copying of previous successful innovations. The investigation of the welfare and policy consequences of pursuing successful lines versus experimenting with new, untried research lines is an interesting and underresearched area.

#### APPENDIX A: OMITTED PROOFS

##### PROOF OF LEMMA 1:

The proof comprises three steps. First, we show that  $t = 0$  belongs to the support of mixing time (so that there is no time interval with zero probability of experimentation). Suppose, to obtain a contradiction, that  $t_1 = \inf\{t: \lambda(t) > 0\} > 0$ . Then, because experimenting after  $t_1$  is in the support of the mixed-strategy equilibrium, equilibrium payoffs must satisfy

$$V_1 = e^{-rt_1} p \Pi_2.$$

Now consider deviation where firm  $i$  chooses  $\lambda(0) = +\infty$ . This has payoff

$$V_0 = p \Pi_2 > V_1$$

for any  $t_1 > 0$ , yielding a contradiction.

Second, we show that there does not exist  $T < \infty$  such that the support of the stopping time  $\tau$  (induced by  $\lambda$ ) is within  $[0, T]$ . Suppose not, then it implies that there exists  $t \in [0, T]$  such that  $\lambda(t) = +\infty$  and let  $t_1 = \inf\{t: \lambda(t) = +\infty\}$ . This implies

that the payoff to both firms once the game reaches time  $t_1$  without experimentation (which has positive probability since  $t_1 = \inf\{t: \lambda(t) = +\infty\}$ ) is

$$V(\tau = t_1) = e^{-rt_1} p \Pi_2$$

(where  $V(\tau = t)$ , or  $V(t)$ , denotes present discounted value as a function of experimentation time). Now consider a deviation by firm  $i$  to strategy  $\tau'$ , which involves waiting for  $\epsilon > 0$  after the game has reached  $t_1$  and copying a successful project by firm  $\sim i$  (if there is such a success). This has payoff

$$V(\tau') = e^{-r(t_1+\epsilon)} [p \Pi_2 + (1-p)p \Pi_1]$$

since firm  $\sim i$  is still  $\lambda(t_1) = +\infty$  and will thus experiment with probability 1 at  $t_1$ . Assumption 1 implies that  $V(\tau')$  is strictly greater than  $V(\tau = t_1)$  for  $\epsilon$  sufficiently small.

Finally, we show that  $\lambda(t) > 0$  for all  $t$ . Again suppose, to obtain a contradiction, that there exist  $t_1$  and  $t_2 > t_1$  such that  $\lambda(t) = 0$  for  $t \in (t_1, t_2)$ . Then, with the same argument as in the first part, the payoff from the candidate equilibrium strategy  $\tau$  to firm  $i$  conditional on no experimentation until  $t_1$  is

$$V(\tau) = e^{-rt_2} p \Pi_2.$$

However, deviating and choosing  $\tau' = t_1$  yields

$$V(\tau' = t_1) = e^{-rt_1} p \Pi_2 > V(\tau).$$

This contradiction completes the proof of the lemma.

#### PROOF OF PROPOSITION 12:

The proof consists of two main steps. The first involves characterizing the equilibrium with two firms when  $p$  has support  $[a, b] \subset [0, \beta]$ . The second involves extending the characterization of equilibrium to the more general case when the support of  $G$  is  $[a, b] \subset [0, 1]$ .

**Step 1:** We show that under the assumption that  $[a, b] \subset [0, \beta]$ , there exists a symmetric equilibrium represented by a strictly decreasing function  $\tau(p)$  with  $\tau(b) = 0$  which maps signals to time of experimentation provided that the other player has not yet experimented. Proposition 15 formalizes this idea and is proved by using a series of lemmas.

**PROPOSITION 15:** *Suppose that the support of  $G$  is  $[a, b] \subset [0, \beta]$ . Define*

$$(25) \quad \tau(p) = \frac{1}{r\beta} \left[ \log G(b)(1-b) - \log G(p)(1-p) + \int_p^b \log G(z) dz \right].$$

Then the unique symmetric equilibrium takes the following form:

- 1) each firm copies a successful innovation and immediately experiments if the other firm experiments unsuccessfully;
- 2) firm  $i$  with signal quality  $p_i$  experiments at time  $\tau(p_i)$  given by (25) unless firm  $\sim i$  has experimented before time  $\tau(p_i)$ .

PROOF:

The proof uses the following lemmas.

LEMMA 4:  $\tau(p)$  cannot be locally constant. That is, there exists no interval  $P = [\bar{p}, \bar{p} + \epsilon]$  with  $\epsilon > 0$  such that  $\tau(p) = t$  for all  $p \in P$ .

PROOF:

Suppose, to obtain a contradiction, that the equilibrium involves  $\tau(p) = t$  for all  $p \in P$ . Then, let  $p_i \in P$ . Firm  $i$ 's (time  $t$ ) payoff after the game has reached (without experimentation) time  $t$  is

$$v(t|p_i) = p_i[(G(\bar{p} + \epsilon) - G(\bar{p}))\Pi_1 + (1 - G(\bar{p} + \epsilon) + G(\bar{p}))\Pi_2],$$

since with probability  $G(\bar{p} + \epsilon) - G(\bar{p})$  firm  $\sim i$  has  $p \in P$  and thus also experiments at time  $t$ . In this case, firm  $i$ , when successful, is not copied and receives  $\Pi_1$ . With the complementary probability, it is copied and receives  $\Pi_2$ . Now consider the deviation  $\tau(p_i) = t + \delta$  for  $\delta > 0$  and arbitrarily small. The payoff to this is

$$\begin{aligned} v_d(t|p_i) &= e^{-r\delta}[(G(\bar{p} + \epsilon) - G(\bar{p}))(\zeta\Pi_2 + (1 - \zeta)p_i\Pi_1) \\ &\quad + (1 - G(\bar{p} + \epsilon) + G(p_i))p_i\Pi_2], \end{aligned}$$

where  $\zeta \equiv E[p|p \in P]$  is the expected probability of success of a firm with type in the set  $P$ . Since  $\Pi_2 > p_i\Pi_1$ , we have  $\zeta\Pi_2 + (1 - \zeta)p_i\Pi_1 > p_i\Pi_1$ . Moreover, by the assumption that  $G$  has strictly positive density,  $G(\bar{p} + \epsilon) - G(\bar{p}) > 0$ . Thus for  $\delta$  sufficiently small, the deviation is profitable. This contradiction establishes the lemma.

LEMMA 5:  $\tau(p)$  is continuous in  $[a, b]$ .

PROOF:

Suppose  $\tau(p)$  is discontinuous at  $\bar{p}$ . Assume without loss of generality that  $\tau(\bar{p}+) \equiv \lim_{\epsilon \downarrow 0} \tau(\bar{p} + \epsilon) > \tau(\bar{p}-) \equiv \lim_{\epsilon \uparrow 0} \tau(\bar{p} - \epsilon)$ . Then firms with signal  $p = \bar{p} + \delta$  for sufficiently small  $\delta > 0$  can experiment at time  $\tau(\bar{p}-) + \epsilon$  for  $\epsilon < \tau(\bar{p}+) - \tau(\bar{p}-)$  and increase their payoff since  $r > 0$ .

LEMMA 6:  $\tau(p)$  is strictly monotone on  $[a, b]$ .

PROOF:

Suppose, to obtain a contradiction, that there exist  $q_1 > q_2$  such that  $\tau(q_1) = \tau(q_2) = \bar{\tau}$ . Suppose that  $\sim i$  follows the equilibrium strategy characterized by  $\tau(p)$  and consider firm  $i$ 's expected profit when  $p_i = q$  and it chooses to experiment at time  $t$ . This can be written as

$$(26) \quad V(q, t) = \int_{p \in P_{before}^t} e^{-r\tau(p)} (p\Pi_2 + (1 - p)q\Pi_1) dG(p) \\ + e^{-r\tau} q\Pi_2 \int_{p \in P_{after}^t} dG(p),$$

where  $P_{before}^t = \{p: \tau(p) \leq t\}$  and  $P_{after}^t = \{p: \tau(p) > t\}$ . Notice that  $V(q, t)$  is linear in  $q$ .

For  $\tau(p)$  to characterize a symmetric equilibrium strategy and given our assumption that  $\tau(q_1) = \tau(q_2) = \bar{\tau}$ , we have

$$(27) \quad V(q_1, \bar{\tau}) \geq V(q_1, t') \text{ and } V(q_2, \bar{\tau}) \geq V(q_2, t')$$

for all  $t' \in \mathbb{R}_+$ .

Now take  $q = \alpha q_1 + (1 - \alpha)q_2$  for some  $\alpha \in (0, 1)$ . By the linearity of  $V(q, t)$ , this implies that for any  $t \neq \bar{\tau}$ , we have

$$V(\alpha q_1 + (1 - \alpha)q_2, t) = \alpha V(q_1, t) + (1 - \alpha)V(q_2, t) \\ \leq \alpha V(q_1, \tau(q_1)) + (1 - \alpha)V(q_2, \tau(q_2)) \\ = V(\alpha q_1 + (1 - \alpha)q_2, \bar{\tau}),$$

where the middle inequality exploits (27). This string of inequalities implies that  $\tau(\alpha q_1 + (1 - \alpha)q_2) = \bar{\tau}$  for  $\alpha \in [0, 1]$ . Therefore,  $\tau$  must be constant between  $q_1$  and  $q_2$ . But this contradicts Lemma 4, establishing the current lemma.

The three lemmas together establish that  $\tau$  is continuous and strictly monotone. This implies that  $\tau$  is invertible, with inverse  $\tau^{-1}(t)$ . Moreover,  $\tau(b) = 0$ , since otherwise a firm with signal  $b - \epsilon$  could experiment earlier and increase its payoff. Now consider the maximization problem of firm  $i$  with signal  $q$ . This can be written as an optimization problem where the firm in question chooses the threshold signal  $p = \tau^{-1}(t)$  rather than choosing the time of experimentation  $t$ . In particular, this maximization problem can be written as

$$(28) \quad \max_{p \in [a, b]} \int_p^b e^{-r\tau(p \sim i)} (p \sim i \Pi_2 + (1 - p \sim i)q \Pi_1) dG(p \sim i) + e^{-r\tau(p)} G(p)q \Pi_2,$$

where the first term is the expected return when the firm  $\sim i$  has signal quality  $p_{\sim i} \in [p, b]$  and the second term is the expected return when  $p_{\sim i} < p$ , so that firm  $\sim i$  will necessarily copy from  $i$ 's successful innovation.

Next, suppose that  $\tau$  is differentiable (we will show below that  $\tau$  must be differentiable). Then the objective function (28) is also differentiable and the first-order optimality condition can be written (after a slight rearrangement) as

$$r\tau'(p) = \frac{g(p)}{G(p)} \left[ 1 - \frac{p}{q} - (1 - p)\beta^{-1} \right].$$

In a symmetric equilibrium, the function  $\tau(p)$  must be a best response to itself, which here corresponds to  $p = q$ . Therefore, when differentiable,  $\tau(p)$  is a solution to

$$(29) \quad r\tau'(p) = \frac{g(p)}{G(p)} (1 - p)\beta^{-1}.$$

Integrating this expression, then using integration by parts and the boundary condition  $\tau(b) = 0$ , we obtain the unique solution (when  $\tau(p)$  is differentiable) as

$$\begin{aligned} \tau(p) &= \frac{1}{r\beta} \int_p^b (1 - z) \frac{g(z)}{G(z)} dz \\ &= \frac{1}{r\beta} \left[ \log G(b)(1 - b) - \log G(p)(1 - p) + \int_p^b \log G(z) dz \right]. \end{aligned}$$

To complete the proof, we need to establish that this is the unique solution. Lemmas 5 and 6 imply that  $\tau(p)$  must be continuous and strictly monotone. The result follows if we prove that  $\tau(p)$  is also differentiable. Recall that a monotone function is differentiable almost everywhere, i.e., it can have at most a countable number of points of non-differentiability (see, for example, Gerald B. Folland 1984, 101, Theorem 3.23). Take  $\bar{p}$  to be a point of non-differentiability. Then there exists some sufficiently small  $\epsilon > 0$  such that  $\tau(p)$  is differentiable on  $(\bar{p} - \epsilon, \bar{p})$  and on  $(\bar{p}, \bar{p} + \epsilon)$ . Then (29) holds on both of these intervals. Integrating it over these intervals, we obtain

$$\tau(p) = \tau(\bar{p} - \epsilon) - \frac{1}{r\beta} \int_{\bar{p}-\epsilon}^p (1 - z) \frac{g(z)}{G(z)} dz \quad \text{for } p \in (\bar{p} - \epsilon, \bar{p}), \text{ and}$$

$$\tau(p) = \tau(\bar{p}) - \frac{1}{r\beta} \int_{\bar{p}}^p (1 - z) \frac{g(z)}{G(z)} dz \quad \text{for } p \in (\bar{p}, \bar{p} + \epsilon).$$

Now taking the limit  $\epsilon \rightarrow 0$  on both intervals, we have either (i)  $\tau(\bar{p}+) \neq \tau(\bar{p}-)$ ; or (ii)  $\tau(\bar{p}+) = \tau(\bar{p}-)$ . The first of these two possibilities contradicts continuity, so (ii) must apply. But then  $\tau(\bar{p})$  is given by (25) and is thus differentiable. This argument establishes that  $\tau(p)$  is differentiable everywhere and proves the uniqueness of equilibrium.



**Step 2:** To complete the proof of Proposition 12, we need to consider the more general case when the support of  $G$  is  $[a, b] \subset [0, 1]$ . This consists of the showing three additional claims. First, we show that firms with  $p \geq \beta$  will always experiment before firms with  $p \in [a, \beta)$ . The claim follows by a single-crossing argument. First, recall that the value of experimenting at time  $t$  for a firm with  $p \in [a, \beta)$  is given by (26). Defining  $P'_{+after\wedge\beta+} = \{p: \tau(p) > t \text{ and } p \geq \beta\}$  and  $P'_{-after\wedge\beta-} = \{p: \tau(p) > t \text{ and } p < \beta\}$ , the value of experimenting for a firm with  $q \in [a, \beta)$  can be rewritten as

$$(30) \quad V(q, t) = q\Pi_2 \left\{ \int_{p \in P'_{before}} e^{-r\tau(p)} \left( \frac{p}{q} + \frac{1-p}{\beta} \right) dG(p) + e^{-rt} \left[ \frac{1}{\beta} \int_{p \in P'_{after\wedge\beta+}} dG(p) + \int_{p \in P'_{after\wedge\beta-}} dG(p) \right] \right\},$$

which exploits the fact that when  $p \in P'_{before}$  or when  $p \in P'_{after\wedge\beta+}$ , there will be no copying, and when  $p \in P'_{after\wedge\beta-}$ , the innovation (which takes place again with probability  $q$ ) will be copied, for a payoff of  $\Pi_2 = \beta\Pi_1$ .

Next, turning to firms with  $p = q' \geq \beta$ , recall that these firms prefer not to copy prior successful experimentation (from Lemma 3). Therefore, their corresponding value can be written as

$$(31) \quad \tilde{V}(q', t) = q'\Pi_2 \left\{ \frac{1}{\beta} \int_{p \in P'_{before}} e^{-r\tau(p)} dG(p) + e^{-rt} \left[ \frac{1}{\beta} \int_{p \in P'_{after\wedge\beta+}} dG(p) + \int_{p \in P'_{after\wedge\beta-}} dG(p) \right] \right\}.$$

Note also that when the experimentation time is reduced, say from  $t$  to  $t' < t$ , the first integral gives us the cost of such a change and the second expression ( $e^{-rt}$  times the square bracketed term) gives the gain. Now the comparison of (30) to (31) establishes the single-crossing property, meaning that at any  $t$  a reduction to  $t' < t$  is always strictly more valuable for  $q' \geq \beta$  than for  $q \in [a, \beta)$ . First, the gains, given by the expression in (30) and (31), are identical. Second, the term in parentheses in the first integral in (30) is a convex combination of  $1/q > 1/\beta$  and  $1/\beta$ , and thus is strictly greater than  $1/\beta$ , so that the cost is always strictly greater for  $q \in [a, \beta)$  than for  $q' \geq \beta$ . From this strict single-crossing argument, it follows that there exists some  $T$  such that  $\tau(p) \leq T$  for all  $p \geq \beta$  and  $\tau(p) > T$  for all  $p \in [a, \beta)$ .

The second claim establishes that all firms with  $p \geq \beta$  will experiment immediately, that is,  $\tau(p) = 0$  for all  $p \geq \beta$ . To show this, first note that all terms in (31) are multiplied by  $q' \geq \beta$ , so the optimal set of solutions for any firm with  $p \geq \beta$  must be identical. Moreover, since  $\tau(p) > T$  for all  $p \in [a, \beta)$ ,  $P'_{after\wedge\beta-}$  is identical for all  $t \in [0, T]$ , and  $t > 0$  is costly because  $r > 0$ . Therefore, the unique optimal strategy for all  $p \geq \beta$  is to experiment immediately. Therefore,  $\tau(p) = 0$  for all  $p \geq \beta$ .

Finally, we combine the equilibrium behavior of firms with  $p \geq \beta$  with those of  $p \in [a, \beta)$ . First, suppose that  $b \leq \beta$ . Then the characterization in Proposition 15 applies exactly. Next suppose that  $b > \beta$ , so that some firms might have signals  $p \geq \beta$ . The previous step of the proof has established that these firms will experiment immediately. Subsequently, firms with  $p \in [a, \beta)$  will copy a successful innovation at time  $t = 0$  or experiment if there is an unsuccessful experimentation at  $t = 0$ . If there is no experimentation at  $t = 0$ , then equilibrium behavior (of firms with  $p \in [a, \beta)$ ) is given by Proposition 15, except that the upper support is now  $\beta$  and the relevant distribution is  $G(p)$  conditional on  $p \in [a, \beta)$ , thus all terms are divided by  $G(\beta)$ . This completes the proof of Proposition 12.

#### PROOF OF PROPOSITION 13:

The proof mimics that of Proposition 12, with the only difference being that the maximization problem of firm  $i$ , with signal  $p_i = q$ , is now modified from (28) to

$$\begin{aligned} \max_{p \in [a, b]} \int_p^b e^{-r\tau(p_{\sim i})} (p_{\sim i}(\Pi_2 - \eta) + (1 - p_{\sim i})q\Pi_1) dG(p_{\sim i}) \\ + e^{r\tau(p)} G(p) q(\Pi_2 + \eta), \end{aligned}$$

which takes into account that copying has cost  $\eta$  and if firm  $i$  is the first innovator, then it will be copied and will receive  $\eta$ . Repeating the same argument as in Proposition 12 establishes that the unique equilibrium is given by (24).

To prove the second part of the proposition, first suppose that  $b < p^\eta$  and  $b < p^\eta$  so that  $\bar{b} = b$  in both cases. Recall also that  $\tau^\eta(p) = \bar{\tau}^\eta(p) > 0$  for  $p \in [a, p^\eta)$ .  $p^\eta$  is decreasing in  $\eta$ , so that  $\tau^\eta(p) = 0$  implies that  $\bar{\tau}^\eta(p) = 0$  for any  $\eta' > \eta$ . We therefore only need to show that  $\bar{\tau}^\eta(p)$  is strictly decreasing for all  $p \in [a, p^\eta)$ . Since  $\bar{\tau}^\eta(p)$  is differentiable, it is sufficient to show that its derivative with respect to  $\eta$  is negative. This follows by differentiating (24) (with  $\bar{b} = b$ ). In particular,

$$\frac{d\tau^\eta(p)}{d\eta} = -\frac{1}{(\Pi_2 + \eta)} \left[ \bar{\tau}^\eta(p) + \frac{2}{rG(\bar{b})} (\log G(\bar{b}) - \log G(p)) \right] < 0,$$

since  $\log G(\bar{b}) > \log G(p)$  and  $\bar{\tau}^\eta(p) > 0$ .

Next, suppose that  $b > p^\eta$ . In that case  $\bar{b} = p^\eta$  and  $d\tau^\eta(p)/d\eta$  (in the neighborhood of  $\eta'$ ) will include additional terms because of the effect of  $\eta$  on  $\bar{b}$ . In particular:

$$\begin{aligned} (32) \quad \frac{d\tau^{\eta'}(p)}{d\eta} = & -\frac{1}{(\Pi_2 + \eta')} \left[ \bar{\tau}^{\eta'}(p) + \frac{2}{rG(p^{\eta'})} (\log G(p^{\eta'}) - \log G(p)) \right] \\ & - \frac{g(p^{\eta'})}{G(p^{\eta'})\Pi_1} \frac{\Pi_1 - 2\eta' - p^{\eta'}\Pi_1}{r(\Pi_2 + \eta')G(p^{\eta'})} + \frac{g(p^{\eta'})}{G(p^{\eta'})\Pi_1} \bar{\tau}^{\eta'}(p). \end{aligned}$$

The first line is again strictly negative and so is the first expression in the second line. The second expression in the second line could be positive, however. For given  $\eta'$ , this term is decreasing in  $p$  and tends to 0 as  $p$  approaches  $p^{\eta'}$  (from (24)). Therefore, there exists  $p^*(\eta')$  such that for  $p \geq p^*(\eta')$ , it is no larger than the first term in the second line. This establishes that for  $p \in [p^*(\eta'), p^{\eta'}]$ ,  $\tau^{\eta'}(p)$  is again decreasing in  $\eta$ , completing the proof.

#### APPENDIX B: EQUILIBRIUM WITH PRIVATE SIGNALS AND MULTIPLE FIRMS

We now extend the analysis of the private and heterogeneous signals environment from Section IV to the case with multiple firms. In particular, we show that all equilibria are payoff equivalent for all players and involve firms with strong signals ( $p_i \geq \beta$ ) experiment first. We also discuss briefly the structure of those equilibria and provide an explicit characterization of the unique mixed equilibrium, when all firms with signals  $\geq \beta$  use the same experimentation strategy.

**PROPOSITION 16:** *Suppose that there are  $N \geq 3$  firms and the support of  $G$  satisfies  $[a, b] \not\subset [0, \beta]$ . Then:*

- 1) *There does not exist a symmetric equilibrium in which all firms with  $p \geq \beta$  experiment at  $t = 0$ .*
- 2) *All symmetric equilibria involve firms with  $p \geq \beta$  experimenting in the time interval  $[0, T]$  and the rest of the firms experiment after  $T$  (if there is no prior experimentation) for some  $T > 0$ .*
- 3) *All symmetric equilibria take the following form:*
  - (a) *Firms with  $p \geq \beta$  experiment in time interval  $[0, T]$  with flow rate of experimentation  $\xi(p, t)$ .*
  - (b) *If there is not any prior experimentation, a firm with signal  $p_i < \beta$  experiments at time  $\tau(p_i) > T$ , where  $\tau(\cdot)$  is a strictly decreasing function.*

*Moreover, all such equilibria are payoff equivalent for all players.*

Note that the characterization of Part 3 allows for pure strategies from firms with strong signals ( $p \geq \beta$ )—in fact there is such an equilibrium.

**PROOF:**

**Part 1:** Suppose that  $N = 3$ , and that  $\Pi_2 = \Pi_3$ . Suppose, to obtain a contradiction, that there exists a symmetric equilibrium where all firms with  $p \geq \beta$  experiment at  $t = 0$ . Consider firm  $i$  with  $p_i > \beta$ . Let  $\chi_0$  be the probability that none of the other two firms have  $p \geq \beta$ ,  $\chi_1$  be the probability that one of the other two firms has  $p \geq \beta$  and  $\chi_2$  be the probability that both firms have  $p \geq \beta$ . Let us also define

$\zeta = \mathbb{E}[p|p \geq \beta]$ . Since  $p_i > \beta$ , by hypothesis, firm  $i$  experiments at time  $t = 0$ . Its expected payoff is

$$V(p_i, 0) = \chi_0 p_i \Pi_2 + \chi_1 p_i \left[ \zeta \left( \frac{\Pi_1}{2} + \frac{\Pi_2}{2} \right) + (1 - \zeta) \Pi_2 \right] + \chi_2 p_i \Pi_1.$$

Intuitively, when none of the other two firms have  $p \geq \beta$ , when successful, the firm is copied immediately, receiving payoff  $\Pi_2$ . When both of the other two firms have  $p \geq \beta$ , there is no copying, so when successful, firm  $i$  receives  $\Pi_1$ . When one of the other two firms has  $p \geq \beta$ , then this other firm also experiments at time  $t = 0$  and is successful with probability  $\zeta = \mathbb{E}[p|p \geq \beta]$ . In that case, in a symmetric equilibrium the third firm copies each one of the two successful innovations with probability  $1/2$ . With the complementary probability,  $1 - \zeta$ , the other firm with  $p \geq \beta$  is unsuccessful, and the third firm necessarily copies firm  $i$ .

Now consider the deviation to wait a short interval  $\epsilon > 0$  before innovation. This will have payoff

$$\begin{aligned} \lim_{\epsilon \downarrow 0} V(p_i, \epsilon) &= \chi_0 p_i \Pi_2 + \chi_1 p_i (\zeta \Pi_1 + (1 - \zeta) \Pi_2) + \chi_2 p_i \Pi_1 \\ &> V(p_i, 0). \end{aligned}$$

The first line of the previous expression follows since, with this deviation, when there is one other firm with  $p \geq \beta$ , the third firm necessarily will copy the first innovator. The inequality follows since  $\Pi_1 > \Pi_2$ , establishing that there cannot be an equilibrium in which all firms with  $p \geq \beta$  experiment at time  $t = 0$ . This argument generalizes, with a little modification, to cases in which  $N > 3$  and  $\Pi_n$ s differ.

**Part 2:** Part 2 follows from a single crossing argument similar to the one used in the proof of Proposition 12.

**Part 3 (Sketch):** We give an argument for why all equilibria are payoff equivalent for all players. Consider firms with strong signals, i.e., firms such that  $p \geq \beta$ . Note that  $\xi(p, t) > 0$  for at least some  $p$  for all  $t \in [0, T]$ . It is evident now from (31) in the proof of Proposition 15 that all firms with signal  $p \geq \beta$  have to be indifferent between experimenting at any time  $t$  in  $[0, T]$  and, in particular, between experimenting at  $t$  and at 0. Combined with Part 1, this implies that the expected payoff of a firm with signal  $p \geq \beta$  is equal to

$$p \Pi_1 \mathbb{P}(p_i \geq \beta, \text{ for all } i) + p \Pi_2 (1 - \mathbb{P}(p_i \geq \beta, \text{ for all } i)),$$

in all equilibria (no matter what the equilibrium strategy profile is). Similarly, we can show that the expected payoff for the rest of the firms (firms with weak signals) is also the same in all equilibria.

In Proposition 16, we did not explicitly describe any equilibrium. Proposition 17 provides a characterization of the unique mixed-strategy equilibrium, when firms with signals  $p \geq \beta$  use the same experimentation strategy, i.e., the rate of experimentation for those firms depends only on time  $t$  (not their signal quality),  $\xi(p, t) = \xi(t)$ .

To simplify the exposition, we focus on an economy in which  $N = 3$  and  $G$  is uniform on  $[0, 1]$ . The characterization result in this proposition can be (in a relatively straightforward way) extended to  $N > 3$ . We also conjecture that it can be extended to any distribution  $G$ , though this is less trivial.

**PROPOSITION 17:** *Consider an economy with  $N = 3$  firms,  $\Pi_2 = \Pi_3$  and  $G$  uniform over  $[0, 1]$ . Then, the following characterizes the unique symmetric equilibrium, when firms with signals  $p \geq \beta$  use the same experimentation strategy.*

- 1) *Firms with  $p \geq \beta$  experiment at the flow rate  $\xi(t)$  as long as no other firm has experimented until  $t$ . They experiment immediately following another (successful or unsuccessful) experiment. There exists  $T < \infty$  such that*

$$e^{-\int_0^T \xi(t) dt} = 0.$$

*That is, all firms with  $p \geq \beta$  will have necessarily experimented within the interval  $[0, T]$  (or equivalently,  $\lim_{t \rightarrow T} \xi(t) = +\infty$ ).*

- 2) *Firms with  $p < \beta$  immediately copy a successful innovation and experiment at time  $\tilde{\tau}_2(p)$  following an unsuccessful experimentation and at time  $\tilde{\tau}_3(p)$  if there has been no experimentation until time  $T$ .*

**PROOF:**

Let us define  $\mu(t)$  as the probability that firm  $\sim i$  that has not experimented until time  $t$  has  $p_{\sim i} \geq \beta$ . The assumption that  $G$  is uniform over  $[0, 1]$  implies that  $\mu(0) = 1 - \beta$ .

Now consider the problem of firm  $i$  with  $p_i \geq \beta$ . If there has yet been no experimentation and this firm experiments at time  $t$ , its payoff (discounted to time  $t = 0$ ) is

$$V(p_i, t) = p_i e^{-rt} [\Pi_1 \mu(t)^2 + \Pi_2 (1 - \mu(t)^2)],$$

since  $\mu(t)^2$  is the probability with which both other firms have  $p \geq \beta$  and will thus not copy. With the complementary probability, its innovation will be copied. Alternately, if it delays experimentation by some small amount  $dt > 0$ , then its payoff is:

$$\begin{aligned} V(p_i, t + dt) &= p_i e^{-r(t+dt)} [2\bar{p}\xi(t)\mu(t)dt\Pi_1 \\ &+ (1 - 2\xi(t)\mu(t)dt) [\Pi_1 \mu(t + dt)^2 + \Pi_2 (1 - \mu(t + dt)^2)] \\ &+ 2\xi(t)\mu(t)(1 - \bar{p})dt [\Pi_1 \mu(t + dt) + \Pi_2 (1 - \mu(t + dt))]], \end{aligned}$$

where  $\bar{p} \equiv E[p|p > \beta]$  and we use the fact that other firms with  $p \geq \beta$  experiment at the rate  $\xi(t)$ . In a mixed-strategy equilibrium, these two expressions must be equal (as  $dt \rightarrow 0$ ). Setting these equal and rearranging, we obtain

$$(33) \quad \frac{d(\mu^2(t))}{dt} + 2\xi(t)\mu(t)(1 - \mu(t))[\bar{p} + \mu(t)] - r\mu^2(t) = \frac{\Pi_2 r}{\Pi_1 - \Pi_2}.$$

In addition, the evolution of beliefs  $\mu(t)$  given the uniform distribution and flow rate of experimentation at  $\xi(t)$  can be obtained as

$$(34) \quad \mu(t) = \frac{e^{-\int_0^t \xi(\tau) d\tau} (1 - \beta)}{e^{-\int_0^t \xi(\tau) d\tau} (1 - \beta) + \beta}.$$

Now let us define

$$(35) \quad f(t) \equiv e^{-\int_0^t \xi(\tau) d\tau} (1 - \beta).$$

Using (35), (34) can be rewritten as

$$\mu(t) = \frac{f(t)}{f(t) + \beta},$$

which in turn implies

$$f(t) = \frac{\beta\mu(t)}{1 - \mu(t)}.$$

Moreover (35) also implies that

$$(36) \quad \xi(t) = -\frac{f'(t)}{f(t)} = -\frac{\mu'(t)}{(1 - \mu(t))\mu(t)}.$$

Substituting these into (33), we obtain the following differential equation for the evolution of  $\mu(t)$ :

$$2\mu(t)\mu'(t) + 2\xi(t)\mu(t)(1 - \mu(t))[\bar{p} + \mu(t)] - r\mu^2(t) = \frac{r}{\beta^{-1} - 1}.$$

Further substituting  $\xi(t)$  from (36), we obtain

$$\mu'(t) = -\frac{r}{2\bar{p}\beta^{-1} - 1} (1 + (\beta^{-1} - 1)\mu^2(t)).$$

This differential equation satisfies the Lipschitz condition and therefore it has a unique solution, which takes the form

$$\mu(t) = \frac{1}{\sqrt{\beta^{-1} - 1}} \tan\left(\sqrt{\beta^{-1} - 1} \left[ -\frac{r}{2\bar{p}\beta^{-1} - 1} t + \frac{\arctan(\mu(0)\sqrt{\beta^{-1} - 1})}{\sqrt{\beta^{-1} - 1}} \right]\right),$$

with boundary condition  $\mu(0) = 1 - \beta$ . Given this solution, the flow rate of experimentation for firms with  $p \geq \beta$ ,  $\xi(t)$ , is obtained from (36) as

$$\xi(t) = c_1 c_2 (1 + \tan(c_1(-c_2 t + c_3))^2) \left[ -\frac{1}{-c_1 + \tan(c_1(-c_2 t + c_3))} + \frac{1}{\tan(c_1(-c_2 t + c_3))} \right],$$

where

$$c_1 \equiv \sqrt{\beta^{-1} - 1}, c_2 \equiv -\frac{r}{2\bar{p}(\beta^{-1} - 1)}, \text{ and } c_3 \equiv \frac{\arctan(\mu(0)\sqrt{\beta^{-1} - 1})}{\sqrt{\beta^{-1} - 1}}.$$

It can then be verified that

$$\lim_{t \rightarrow T} \xi(t) = \infty,$$

where  $T = c_3/c_2$ . It can also be verified that for all  $t \in [0, T]$ , where firms with  $p \geq \beta$  are experimenting at positive flow rates, firms with  $p < \beta$  strictly prefer to wait. The equilibrium behavior of these firms after an unsuccessful experimentation or after time  $T$  is reached is given by an analysis analogous to Proposition 12. Combining these observations gives the form of the equilibrium described in the proposition.

#### REFERENCES

- Aghion, Philippe, and Peter Howitt.** 1992. "A Model of Growth through Creative Destruction." *Econometrica*, 60(2): 323–51.
- Arrow, Kenneth.** 1962. "Economic Welfare and the Allocation of Resources for Invention." In *The Rate and Direction of Inventive Activity: Economic and Social Factors*, 609–26. Princeton, NJ: Princeton University Press.
- Bolton, Patrick, and Christopher Harris.** 1999. "Strategic Experimentation." *Econometrica*, 67(2): 349–74.
- Bulow, Jeremy, and Paul Klemperer.** 1994. "Rational Frenzies and Crashes." *Journal of Political Economy*, 102(1): 1–23.
- Bulow, Jeremy, and Paul Klemperer.** 1999. "The Generalized War of Attrition." *American Economic Review*, 89(1): 175–89.



- Chamley, Christophe, and Douglas Gale.** 1994. "Information Revelation and Strategic Delay in a Model of Investment." *Econometrica*, 62(5): 1065–85.
- Dasgupta, Partha.** 1988. "Patents, Priority and Imitation or, the Economics of Races and Waiting Games." *Economic Journal*, 98(389): 66–80.
- Earls, Alan R.** 2004. *Images of America: Digital Equipment Corporation*. Portsmouth, NH: Arcadia Publishing.
- Folland, Gerald B.** 1984. *Real Analysis: Modern Techniques and Their Applications*. New York, NY: Wiley-Interscience.
- Fudenberg, Drew, and Jean Tirole.** 1986. "A Theory of Exit in Duopoly." *Econometrica*, 54(4): 943–60.
- Gallini, Nancy, and Suzanne Scotchmer.** 2002. "Intellectual Property: When Is It the Best Incentive System?" In *Innovation Policy and the Economy*, Vol. 2, ed. Adam B. Jaffe, Josh Lerner, and Scott Stern, 51–78. Cambridge, MA: MIT Press.
- Gilbert, Richard, and Carl Shapiro.** 1990. "Optimal Patent Length and Breadth." *RAND Journal of Economics*, 21(1): 106–12.
- Grossman, Gene M., and Elhanan Helpman.** 1991. "Quality Ladders in the Theory of Growth." *Review of Economic Studies*, 58(1): 43–61.
- Gul, Faruk, and Russell Lundholm.** 1995. "Endogenous Timing and the Clustering of Agents' Decisions." *Journal of Political Economy*, 103(5): 1039–66.
- Haigh, John, and Chris Cannings.** 1989. "The n-Person War of Attrition." *Acta Applicandae Mathematicae*, 14(1–2): 59–74.
- Harford, Tim.** 2009. "Why Giant Technological Leaps Aren't Always the Answer." *Financial Times*, July 18, 2009. <http://blogs.ft.com/undercover/2009/07/why-giant-technological-leaps-aren%E2%80%99t-always-the-answer/>.
- Hendricks, Kenneth, and Dan Kovenock.** 1989. "Asymmetric Information, Information Externalities, and Efficiency: The Case of Oil Exploration." *RAND Journal of Economics*, 20(2): 164–82.
- Hendricks, Kenneth, and Robert H. Porter.** 1996. "The Timing and Incidence of Exploratory Drilling on Offshore Wildcat Tracts." *American Economic Review*, 86(3): 388–407.
- Hendricks, Ken, Andrew Weiss, and Charles A. Wilson.** 1988. "The War of Attrition in Continuous Time with Complete Information." *International Economic Review*, 29(4): 663–80.
- Kapur, Sandeep.** 1995. "Technological Diffusion with Social Learning." *Journal of Industrial Economics*, 43(2): 173–95.
- Keller, Godfrey, Sven Rady, and Martin Cripps.** 2005. "Strategic Experimentation with Exponential Bandits." *Econometrica*, 73(1): 39–68.
- Kitch, Edmund W.** 1977. "The Nature and Function of the Patent System." *Journal of Law and Economics*, 20(2): 265–90.
- Klemperer, Paul.** 1990. "How Broad Should the Scope of Patent Protection Be?" *RAND Journal of Economics*, 21(1): 113–30.
- Reinganum, Jennifer F.** 1981. "Dynamic Games of Innovation." *Journal of Economic Theory*, 25(1): 21–41.
- Romer, Paul M.** 1990. "Endogenous Technological Change." *Journal of Political Economy*, 98(5): S71–102.
- Scotchmer, Suzanne.** 1999. "On the Optimality of the Patent Renewal System." *RAND Journal of Economics*, 30(2): 181–96.
- Scotchmer, Suzanne.** 2004. *Innovation and Incentives*. Cambridge, MA: MIT Press.
- Simon, Leo K., and Maxwell B. Stinchcombe.** 1989. "Extensive Form Games in Continuous Time: Pure Strategies." *Econometrica*, 57(5): 1171–1214.
- Smith, J. Maynard.** 1974. "The Theory of Games and the Evolution of Animal Conflicts." *Journal of Theoretical Biology*, 47(1): 209–21.
- Taylor, Curtis R.** 1995. "Digging for Golden Carrots: An Analysis of Research Tournaments." *American Economic Review*, 85(4): 872–90.
- Tirole, Jean.** 1988. *The Theory of Industrial Organization*. Cambridge, MA: MIT Press.