Rational parasites

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Abstract

Understanding the impact of legal protection on investment is of major importance. This paper provides a framework for addressing this issue, and shows that investment may actually be higher in the absence of legal protection. Focusing on the application to innovation, in an environment where an innovator (the host) repeatedly faces the same imitators (parasites), we show that investment can take place even without patent protection, as parasites limit their imitation to preserve the innovator's incentives to invest. We show further that an innovator might be more active without legal protection: it is forced to increase its investment to keep the parasites satisfied and, thus, cooperative. We provide experimental evidence consistent with the theoretical results: in the experiment, investment levels with and without legal protection are comparable, and sometimes greater without patents. Our framework is general enough to apply to other situations such as investment in developing countries, commons' management and long-distance trade.

1 Introduction

Understanding the way in which a reliance on informal institutions, as opposed to legal rules, affects investment choices is of major importance. Case studies have shown how the emergence of social norms substituting for weak legal structures can encourage investment. For instance, Greif (1993 and 1999) finds that social norms in medieval times were able to sustain long-distance trade in the absence of contract enforcement by courts. Ostrom (2009) shows that local arrangements often overcome the commons problem better than central government enforcement. In this paper, we also argue that vigorous investment can take place without formal protection. Moreover, the absence of such protection may even foster greater investment.

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The key idea is that high levels of investments facilitate the emergence of norms substituting for legal rules. That is, while cooperation enables better outcomes, the converse is also true: better (anticipated) outcomes enable the cooperation in the first place. In our model, an investor and parasitical agents, who can potentially expropriate the stochastic outcome of the investment, interact repeatedly. In the absence of legal protection, the parasites rationally choose not to be too aggressive, in an effort to preserve the investor's incentives to invest – parasites refrain from killing their host. Reciprocally, the innovator may invest more than it would with legal protections, in order to augment the promise of future earnings and keep the parasites satisfied and cooperative.[1]

Although the applications are numerous, we develop our ideas specifically in the context of innovation.[2] Recently, there has been a renewed debate on the use of patents to encourage investments in innovation (Boldrin and Levine 2008). We show that legal protection is not necessary for positive levels of investment, and that the absence of patents may even lead to more innovation. There is some empirical evidence consistent with this idea. In particular, Boldrin and Levine (2008) and Bessen and Hunt (2007) argue that the software industry was more innovative before the introduction of patents.[3]

Staying with software, consider the example of Red Hat, a hugely successful company created in 1993. At its stock market introduction, Red Hat was one of the biggest IPOs in the NASDAQ and, since 2009, has been part of the S&P500, with over 3000 employees and revenues of over 500 million dollars. For many, this success is puzzling, since the company's business model is based on open source software. Most of Red Hat's revenues come from the sale to companies of subscriptions, including their own pre-compiled version of the open source operating system Linux, called Red Hat Enterprise Linux, and support services.[4] Two facts are particularly striking. First, as acknowledged in Red Hat's annual report: "anyone can copy, modify and redistribute Red Hat Enterprise Linux (...) however they are not permitted to refer to these products as Red Hat". Numerous clones do indeed exist, but they appear to avoid competing aggressively and do not gain much market share. Second, in spite of a potentially extremely competitive environment, Red Hat invests a lot in research. According to a report from the Linux Foundation, Red Hat is the biggest single contributor

[1]Our explanation for the success of local arrangements should be seen as complementary to Ostrom's notion that local protocols perform well because they are better adapted to particular conditions and better accepted by the community.

[2]The dilemma facing a company opening a factory in a developing country with the risk of expropriation is another important application.

[3]In the United States, the patenting of software began with the Supreme Court decision Diamond vs Diehr in 1981. In previous rulings, the Supreme Court had judged software to be unpatentable.

[4]According to Red Hat's annual report, the revenues from subscriptions in 2010 were $\$541M$ out of a total revenue of $\$652M$.

to the Linux Kernel (excluding unaffiliated contributors), and pays the salaries of many of the top contributing individuals.

It seems plausible that clones of Red Hat rationally choose not to be too aggressive, in an effort to preserve Red Hat's incentives to keep investing in research. Indeed, the manager of a clone declared in an interview, "We have the utmost respect for Red Hat and everything they have done for the community over the years. We have absolutely no desire to upset them" (Kerner 2005). At the same time, Red Hat may, in the absence of patents, innovate more than it would have in their presence, in order to maintain clones' incentive not to be too aggressive.[5]

While this example and the empirical evidence are suggestive, inferring a causal relation between the absence of patents and high investment is challenging, given that we cannot observe the investment levels under the counter-factual scenario. Therefore, after developing our theory we provide some controlled experimental evidence capable of overcoming the identification challenge by artificially creating two different institutional environments, one with patents and one without. Consistent with our theoretical intuition, the average investment in the treatments reproducing the legal monopoly environment is (slightly) lower than in the treatments with no legal protection, as shown in figure 1. Furthermore, the pricing behavior observed in the experiment is coherent with our theory. To the best of our knowledge this is the first experiment designed to compare the levels of investment with and without protection, and this can become a promising avenue of research for providing evidence on an issue extremely difficult to test with field data.[6]

The basic structure of our theoretical model is as follows. A serial innovator initially makes a capital investment in innovative capabilities. This initial investment determines the likelihood that the firm successfully innovates in subsequent periods and the value of the innovation if it does. There are two regimes, one with patents, where the innovator collects monopoly profits from successful innovations, and one without patents, where n imitators can immediately copy any innovation at no cost. In the latter regime, all $n+1$ firms choose a price and a maximum quantity to supply, allowing for an uneven split of profits, if desired.

We find that any level of investment level that leads to positive profits for the innovator in the presence of patents remains part of an equilibrium in their absence, if firms are

[5]A similar example, described in Raustiala and Sprigman (2006), is the case of the fashion industry. Major designers, such as Prada and Gucci, very regularly produce new innovative collections and take little protection. These innovations requires initial investment in contracting with well known designers. Retailers, such as H&M imitate these designs but in an imperfect way so that the imitation can be distinguished from the original; in other words, they refrain from acting too aggressively.

[6]A similar argument in favour of experiments in economics is given in Falk and Heckman (2009), where the authors focus in particular on the application to employment relations. Meloso at al. (2009) also conduct an experiment capturing innovative behavior where they compare different reward mechanisms.

patient enough. More generally, for moderately patient firms many investment levels will be sustainable, but the imitators may be required to take a small share of profits, so that the innovator finds it worthwhile to invest – a behavior reminiscent of that of clones in the Red Hat example.

The multiplicity of equilibria, which is common in dynamic games, makes precise predictions difficult. Nonetheless, interesting statements can be made. There are circumstances under which all non-degenerate equilibria – equilibria where the innovator invests a positive amount – involve more investment without patents than with them. In particular, this happens in a simple setting as investment gets riskier in a second order stochastic dominance sense. The reason is that with risky technologies the temptation of parasites to deviate from a collusive path following a successful innovation is large, and price wars are hard to avoid. The only solution may be for the innovator to increase its investment, thereby raising the benefits to continued collusion: the innovator is forced to work harder to keep the parasites satisfied. However, increasing investment is beneficial in this way only if it increases the probability of a successful innovation, not just the value of successful innovations.

We do not seek to make explicit welfare statements in this paper. Such results could be derived, but this would require making assumptions about the proportion of the social value of innovations that can be appropriated by innovators. If innovators can fully collect all the social value of their innovations, any additional investment prompted by the removal of protection is welfare-reducing. However, recent evidence suggests the opposite: Bloom et al. (2012) report that the social returns to R&D are at least twice as high as the private returns.

There are a number of papers explaining how innovation may occur in the absence of any kind of formal protection. Some rely on technological constraints such as imitation lags (Scherer and Ross 1990), others on strategic effects (Benoît 1985; Henry and Ponce 2011; Henry and Ruiz-Aliseda 2012). Boldrin and Levine (2002 and 2005) provide a theory of competitive innovation.[7] These papers show, in different environments, that innovation can occur in the absence of formal protection. However, in all these contributions, less innovation is conducted than if the innovator was granted a monopoly.

We suggest an alternative explanation for investments in research in the absence of legal protection. Moreover, we show that our model can give rise to even more innovation without patents. Both these theoretical predictions and the experimental evidence we provide fit with the evidence in Boldrin and Levine (2008).

There are two main reasons suggested in the literature for why environments without patent protection can be associated with more innovation. The first one is based on the

[7] See also Anton and Yao (1994 and 2002) on the transfer of ideas in the absence of legal property rights.

sequential nature of research. Bessen and Maskin (2009) show that if innovation is both sequential (new discoveries build on old ones) and complementary (different researchers use different approaches), the absence of patents may lead to more innovation. Innovators benefit from discoveries by rivals as they can build on them.

The second class of models builds on the "escape the competition effect". Aghion et al. (2001, 2005), examine how product market competition affects innovation and, thus, growth. They examine a model where imitation is not immediate and an innovator can stay ahead of its rivals by successfully investing in research. They find that, at least for initially low levels of competition, increasing product market competition has a positive effect on investments.

Our work also builds on the idea that competition, in our case by imitators, exerts a pressure that forces the innovator to invest more. However, our mechanism is very different. In the growth model, there is increased research to escape the intense competition on the market, as the innovator can stay ahead for some time. Our model does not rely on any type of first-mover advantage. In fact, more research is performed to keep the imitators satisfied and cooperative.

Our paper, as it involves pricing in an environment with repeated interaction, is linked to the vast literature on collusion. It is more particularly related to Rotemberg and Saloner (1986), who study collusion in a stochastic environment over the business cycle. We add investments in this framework. We also model the stochastic return differently, which allows us to characterize the condition on second order stochastic dominance. We discuss this paper more in depth in section 3. In a similar vein, Dal Bo (2007) studies collusion when the interest rate fluctuates.

As we previously noted, though we focus on the application to innovation, the model applies more generally to the comparison of environments with and without legal rules. Former literature has stressed the importance of private-order or informal institutions relying mainly on economic and social sanctions imposed to sustain investment (Williamson 1985). Notably, some historical case have demonstrated the role played by reputation mechanisms (Greif 1989, 1993) in a repeated interaction setting.

Finally, our study adds to the recent experimental literature on cooperation and collusion in infinitely repeated games (early examples include: Roth and Murnigham 1978; Palfrey and Rosenthal 1994; and more recently: Dal Bo 2005; Dreber et al. 2008; Camera and Casari 2009; Aoyagi and Frechette 2009; Dal Bo and Frechette 2011; Cooper and Kuhn, 2011; Bigoni, Potters and Spagnolo 2012). While this literature has mainly focused on understanding both the dynamics of cooperation and the conditions favouring collusion or cooperation in infinitely repeated games, our focus is to compare investment choices under different institutional regimes.

The remainder of the paper is organized as follows. In Section 2, we introduce the model. In Section 3, we characterize the equilibria and derive our main theoretical results. In Section 4, we present the experimental setup and results. All proofs, tables and figures are presented in the appendix.

2 Model

We frame the model and results in terms of investments in innovation. We consider an infinite horizon game. In period 0, an innovative firm, denoted Firm 1, makes a capital stock investment k in research capabilities, such as a research facility.[8] This investment determines the likelihood that the firm successfully innovates in subsequent periods and the value of any resulting innovation. In any single period, the firm randomly develops at most one innovation, which can instantly be brought to market at zero marginal cost. The market value of an innovation degrades over time; for simplicity, we assume that the life span of a new product is exactly one period.[9]

The value of an innovation is measured by the one period monopoly profit π the new product generates, which is randomly drawn from R_+, where we let $\pi = 0$ represent that no (market worthy) innovation has taken place. Given the period 0 investment k, let $F(\pi, k)$ be the cumulative probability distribution of developing an innovation worth π at the beginning of period t. We contrast two situations: one of legal monopoly and one where legal protection is absent.

In the case of legal monopoly, Firm 1 collects monopoly profits on any innovation. If it initially chooses k, in each period there is a random draw of π according to $F(\pi, k)$. The firm thus chooses k to maximize $-k + \sum_{t=1}^{\infty} \delta^t \int_0^{\infty} \pi dF(\pi, k) = -k + \frac{\delta E(\pi|k)}{1-\delta}$, where $E(\pi|k) = \int_0^{\infty} \pi dF(\pi, k) < \infty$. We suppose the maximization problem has a solution.

In the second situation, with no property rights, Firm 1 remains the only firm with the ability to innovate, but there are n firms with imitative capabilities.[10] These firms can immediately reproduce any innovation at zero cost. In practice, there are lags before imitators can copy an innovation, and duplication may be costly and imperfect, but we abstract away from these possibilities, which benefit the innovator, as we are interested in

[8] In a more general model, this stock investment would be complemented by on-going research expenditures. We considered such a model in an earlier version, but this complication does not change our main results.

[9] Thus, in the period a product is brought to market there is a continuous demand curve for it, which reaches zero at a high enough price and a finite value at a price of zero, while, in subsequent periods, the quantity demanded is identically zero.

[10] This fixed group of imitators may have incurred a sunk cost to developing know-how and establishing themselves.

incentives for innovation absent these previously noted factors.[11]

The $n+1$ firms play an infinite horizon game in which they share the same period discount rate δ. As before, in period 0, Firm 1 chooses an investment k. In each period $t \geq 1$, if an innovation of strictly positive value is realized, firms $2, ..., n+1$ immediately imitate. Each firm $i = 1, ..., n+1$ then chooses a price p_i^t for the innovation. In a traditional analysis of homogeneous repeated price competition, when several firms choose the lowest price, demand is equally split among them. There is, however, no reason why firms could not choose to split demand unequally by restricting the quantities they supply. This possibility is usually ignored, both for simplicity and because, in the usual settings, collusion is easiest when firms split demand equally (if all firms have the same discount rate). In our setting, however, where only one firm incurs development costs, it is important to allow firms to split demand unequally, if they so choose.[12] Therefore, in addition to choosing a price, in each period t, each firm i chooses a maximum quantity q_i^t to supply. Demand is rationed among the firms in the following way. All consumers attempt to buy from the firms with the lowest price. If demand at this price is less than total supply, each firm sells a quantity proportional to its supply. If demand exceeds total supply, then each firm charging this price sells up to its chosen quantity. This yields a residual demand curve, upon which rationing is applied at the next lowest price, and so forth.[13]

Formally, let h_t denote the history of play up to date t. At each period t, the strategies are the following:

- In period $t = 0$, Firm 1 chooses k.
- In periods $t \geq 1$
  1. The quality of the period t innovation, π_t, is drawn from $F(\pi, k)$.
  2. Each firm then chooses a price quantity pair $(p_i^t, q_i^t) \in R_+ \times R_+$ as a function of (h_t, π_t).

To simplify the exposition of our results, we restrict our attention to *constant-share* equilibria where, along the equilibrium path, the firms all charge the same price and each

[11] See for instance Scherer and Ross (1980) for non-strategic delays in imitation. There can also be strategic delay by imitators such as in Benoît (1985), Henry and Ponce (2011) and Henry and Ruiz-Aliseda (2012).

[12] Firms picking unequal sharing is coherent with casual evidence, such as the Red Hat case discussed in the introduction, although other explanations of this evidence are also possible.

[13] The rationing rule is formally described in the appendix, although the precise rule is unimportant. For instance, rather than a rationed firm selling a quantity proportional to its supply, each firm could, say, sell the same quantity, subject to capacity constraints.

firm's share of total demand is constant. That is, a *constant-share* equilibrium is a subgame perfect equilibrium in which, for each period t and each firm i,

i) $p_i^t = p^t$, for some $p^t \geq 0$, and

ii) for $q^t(p^t) > 0$, we have $\sum_{i=1}^{n+1} q_i^t = q^t(p^t)$ and $\frac{q_i^t}{q^t(p^t)} = \alpha_i$, for some $\alpha_i \geq 0$, where (abusing notation) $q^t(p^t)$ is consumer demand at a price p^t for the innovation realized in period t.

Thus, in a constant-share equilibrium firm i gets a fixed share α_i of total industry revenue in each period. (For instance, Firm 1 gets $\frac{2}{3}$ of the revenue from any innovation and the other firms each get $\frac{1}{3n}$ of the revenue). Off the equilibrium path, an optimal punishment is for all firms to charge 0 and pick a capacity large enough to supply the market.

An *even-share equilibrium* is a special case of a constant-share equilibrium in which the firms evenly share the revenues from a successful innovation; that is, $\alpha_i = \frac{1}{n+1}$ for $i = 1, .., n+1$.

3 Investments with and without protection

3.1 Equilibria

We start by characterizing the constant-share equilibria in the no-patent game. Consider the realization of an innovation with monopoly profit π in some period. This figure is the maximum total profit from the innovation that the firms could share in that period. However, the firms might not actually be able to share these maximal profits in equilibrium. In particular, if π is unusually high, collusion on the monopoly price may be impossible since firms would have a large incentive to undercut and grab π immediately, at the cost of losing out on the collusive profits from future innovations, which would, on average, be much smaller. Thus, for an innovation with very high monopoly profits, colluding firms may have to charge a lower price than the monopoly price, and, as we will see, there is some maximal industry profit that can be obtained in equilibrium in any single period (see Appendix).[14]

Although firms pick prices and capacities each period, it is more convenient to characterize the equilibrium conditions in terms of the resultant revenues. Note that, since firms $2, ..., n+1$ are identical, if there exists an equilibrium where these firms get different shares of demand, there also exists one where they each get the same share $\alpha_i = \frac{\alpha}{n}$, while Firm 1 gets the share

[14]The equilibria found by Rotemberg and Saloner (1986) have a similar feature, and our framework is similar to the one they use in their study of collusion in the face of uncertain demand, although we add an important element of investment. Other important differences include the fact that our firms choose capacities as well as prices and that we model the problem in terms of a shock on monopoly profits rather than a shock on demand (see footnote 14).

$(1-\alpha)$.[15] The constant-share equilibria can be characterized in the following way:

Proposition 1 *A choice of k by Firm 1 forms part of a constant-share equilibrium if and only if there exists a profit $\widetilde{\pi}$ and a share α such that for all $\pi \leq \widetilde{\pi}$,*

$$\pi \leq \frac{\alpha}{n}\pi + \frac{\delta}{1-\delta}\frac{\alpha}{n}\left(\int_0^{\widetilde{\pi}} \pi dF(\pi,k) + \widetilde{\pi}\left(1-F\left(\widetilde{\pi}\right)\right)\right), \tag{1}$$

$$\pi \leq (1-\alpha)\pi + \frac{\delta}{1-\delta}(1-\alpha)\left(\int_0^{\widetilde{\pi}} \pi dF(\pi,k) + \widetilde{\pi}\left(1-F\left(\widetilde{\pi}\right)\right)\right), \tag{2}$$

and

$$k \leq \frac{\delta}{1-\delta}(1-\alpha)\left(\int_0^{\widetilde{\pi}} \pi dF(\pi,k) + \widetilde{\pi}\left(1-F\left(\widetilde{\pi}\right)\right)\right) \tag{3}$$

The first two conditions state that no firm, be it the imitators or the innovator, ever wants to undercut the other firms in any single period. The third condition guarantees that Firm 1 wants to undertake its investment. The term $\widetilde{\pi}\left(1-F\left(\widetilde{\pi}\right)\right)$ reflects the fact that, for profit realizations π greater than some upperbound $\widetilde{\pi}$, the temptation to deviate is too large if firms attempt to share profits π – instead they split the amount $\widetilde{\pi}$. To see the need for an upperbound, allow for the moment that $\widetilde{\pi}$ could be equal to infinity. Combining inequalities (1) and (2), yields the necessary condition that

$$\widetilde{\pi} \leq \frac{\delta}{1-\delta}\frac{1}{n}\left(\int_0^{\widetilde{\pi}} \pi dF(\pi,k) + \widetilde{\pi}\left(1-F\left(\widetilde{\pi}\right)\right)\right) \tag{4}$$

For any k and distribution function F, let $\widetilde{\pi}^F_{\max} = \{\sup \widetilde{\pi} \text{ s.t. (4) holds}\}$. Since the right hand side of (4) is bounded, $\widetilde{\pi}^F_{\max} < \infty$. The quantity $\widetilde{\pi}^F_{\max}$ provides an upper bound on the single period profit level on which firms can manage to collude when Firm 1 invests k.

3.2 Rational parasites

The environment we consider is one where an innovator cannot stay ahead of its competitors and, at first sight, appears to have little incentive to invest. Nonetheless, since the firms interact repeatedly, if they are sufficiently patient they can avoid destructive competition. Indeed, any investment that would lead to positive profits for an innovator with patents, can be part of an equilibrium in the absence of patents, as shown in the following result.

[15] Consider an equilibrium path in which firms $2, ..., n$ receive differing shares α_i. The path in which each firm receives the same share $\alpha' = \frac{\sum_{i=2}^{n+1}\alpha_i}{n}$ is also an equilibrium.

Proposition 2 *For any $\bar{k}$ such that $E\left(\pi|\bar{k}\right) > 0$, there exists a $\bar{\delta} > 0$ such that, for all $\bar{\delta} \leq \delta < 1$, there is a constant-share equilibrium of the no-patent game in which Firm 1 invests $\bar{k}$.*

This proposition follows from familiar dynamic game reasoning with arbitrarily patient players. With players that are not arbitrarily patient, investment is tricker. The existence of the upperbound $\widetilde{\pi}^F_{\max}$ means that total industry profits may be lower in the no-patent world than the patent world. This fact, combined with the fact that Firm 1 must share the returns from innovating, implies that there may be some investment levels that, while profitable when patents are available, do not form part of an equilibrium without patents.

In the absence of legal protection, there always exists a *degenerate* equilibrium in which Firm 1 chooses not to invest at all and all firms plan to charge a price of zero whenever an innovation is obtained. To sustain a non-degenerate equilibrium, where Firm 1 invests a positive amount, the firms must manage to collude on a positive price following an innovation. Colluding on a positive price is easiest if the firms split the revenues from an innovation equally. That is, the best hope for satisfying both conditions (1) and (2), is to set $\frac{\alpha}{n} = \frac{1}{n+1}$, so that $\alpha_i = \frac{1}{n+1}$ for all i, as in an even-share equilibrium. At the same time, however, Firm 1 must be given sufficient incentive to invest in the first place. That is, condition (3) must also be satisfied, and this condition is relaxed by giving Firm 1 a greater share of the revenues, setting $\frac{\alpha}{n} < \frac{1}{n+1}$ so that $\alpha_1 > \frac{1}{n+1}$. When condition (3) bites, *rational parasites* need to limit their aggressiveness in order to preserve the innovator's incentives to invest, as the story of Red Hat suggests.

To get a feel for how investment possibilities depend on the nature of the innovation technology, consider two research processes characterized by the profit distribution functions F and G, where F second order stochastically dominates G. Integrating the right hand sides of (1), (2) and (3) (4) by parts reveals that all three conditions are harder to satisfy under G than F, so that investing without patents is harder with riskier innovations (Proposition 3 below).[16] By the same token, $\widetilde{\pi}^G_{\max} \leq \widetilde{\pi}^F_{\max}$ (see Appendix), so that less industry profit can be made with riskier innovations.

Proposition 3 *Suppose that with an innovation technology characterized by the distribution G, there is a constant-share equilibrium in which Firm 1 invests $\bar{k}$. Then with an innovation characterized by the distribution F, where F second order stochastically dominates G, there is also a constant-share equilibrium in which Firm 1 invests $\bar{k}$.*

[16]Similar reasoning shows that mean-preserving spreads makes collusion more difficult in the framework of Rotemberg and Saloner, although the way they model uncertainty does not allow them to reach this conclusion.

Proposition 3 provides is a testable prediction of the model, which we explore in our experiment. Reading the proposition "in reverse", if we start from an innovation technology for which a particular investment is sustainable and take a series of mean-preserving spreads, we might arrive at a situation where such an investment is no longer possible. As an illustration, suppose that for the distribution F, an investment of $\bar{k}$ yields an innovation worth 10 with probability one, while under G, an investment of $\bar{k}$ yields an innovation worth 0, 10, or 20, with equal probabilities. With patents, these two equal-mean technologies are essentially equivalent. Without patents, however, they are quite different. Suppose the investment $\bar{k}$ is sustainable under F. This implies that under F, the firms can successfully split the amount 10 in each period. However, it might not be possible for the firms to split 20 when it arises under G, since firms have a larger incentive to undercut when the current innovation is worth more. If the firms cannot collude on 20, there is a knock-on effect, and they might not be able to collude on 10 either under G, since the relevant measure for future profits is not the overall mean of 10, but the average over a truncated interval.[17]

How will Firm 1 react if the amount it would have invested with a patent is no longer viable without a patent? The obvious possibility is that Firm 1 invests less, so that it needs to recoup less money. More interestingly, another possibility is that Firm 1 invests more in order to increase the continuation value of the game and make collusion easier. We explore these two possibilities in the next section.

3.3 Investment in innovation with and without protection

We would like to compare investment in innovation when patents are available to investment when they are absent. However, this is often an ambiguous comparison, as there are many equilibria in the no-patent game, some with more innovation, some with less, and we have no compelling criterion for choosing among equilibria. In this section, we examine a special case where unambiguous statements can be made: either all non-degenerate equilibria involve more investment without patents, or all these equilibria involve less investment. In the next section we report on an experiment that models this special case.

For some research, the nature of a successful innovation is not very variable and the investment level mainly influences the frequency of innovations.[18] In line with this, we now assume that the value of a successful innovation is some fixed constant, $\bar{\pi}$, and that

[17]Specifically, if firms cannot collude on 20, to examine whether colluding on 10 is possible, the relevant measure of future profits is not 10 but $\frac{1}{3}0 + \frac{2}{3}10$ since for an outcome of 20, firms are only able to potentially share 10.

[18]Examples include the case of upgrades of software or smartphones, where the issue is mostly one of frequency rather than quality, and also the case of the fashion industry mentioned in the introduction (footnote 3), where the important factor is the speed of introduction of new collections.

investments in research only determine the likelihood $p(k)$ an innovation is developed in any period. Formally, we have that

$$F(\pi, k) = \begin{cases} 1 & \text{if } \pi \geq \bar{\pi} \\ 1 - p(k) & \text{if } 0 \leq \pi < \bar{\pi} \\ 0 & \text{if } \pi < 0 \end{cases}$$

Let k^* be Firm 1's profit-maximizing investment in the presence of patents. Suppose that this investment is not sustainable in the no-patent game. Then, subsequent to a choice of k^*, either (i) in the subgame following a successful innovation, every equilibrium yields zero profits to all firms (collusion is not possible), or (ii) in the subgame following the realization of an innovation, there are equilibria with positive profits, but none of these equilibria yield Firm 1 sufficient expected profits at date zero to warrant the initial investment of k^*.

In the first instance, the problem is that the expected future profits from collusion are not large enough to deter the firms from trying to grab the entire instantaneous profits from a successful innovation. The *only* way to overcome this is for Firm 1 to invest more than k^*, thus raising the probability of a successful innovation in any period and increasing the value of collusion in the continuation game; all non-degenerate equilibria (when these exist) involve more innovation in the absence of patents (see Lemma 1 in the Appendix). In the second instance, while collusive continuation equilibria exist, none of them give Firm 1 enough revenue to cover an investment of k^* at date zero. Now, the *only* possibility for a non-degenerate equilibrium involves Firm 1 saving money by investing less (see Lemma 2).

We now present situations corresponding to (i) and (ii), in which we perform comparative statics that keep the optimal investment under patents (essentially) constant. This allows us to cleanly compare investment levels with and without patents.

An innovation worth $\bar{\pi} = \frac{\pi_0}{m}$ will be developed with probability $p_{m,H}(k) = mh(k - H)$, where $h : R^+ \to [0, 1)$, $h(x) = 0$ for $x \leq 0$, and $h' > 0$. The parameter H is a minimum requirement on the fixed cost that Firm 1 must pay if it wants to conduct any research. Higher H'*s* increase the minimum requirement, but have no effect on the optimal additional investment above this requirement. That is, in the presence of patents, the optimal *incremental* level of investment above H is independent of H, whenever this optimal level is positive. The parameter m varies between 0 and 1. Decreases in m induce a mean-preserving spread on the innovation process and have no effect on the optimal investment, or incremental investment, in the game with patents.

Thus, in the patent game, as m and H vary, the optimal incremental investment, which we again denote k^*, and optimal expected per period revenue, $\pi_0 h(k^*)$, stay constant, whenever k^* remains positive. However, in the no-patent game, the investment k^* gets harder to sustain as m falls (Proposition 3) and as H rises (since Firm 1 must recover its fixed cost). Suppose that for $m = 1, H = 0$, there is an even-share equilibrium ($\alpha_i = \frac{1}{n+1}$ for all i) in which Firm 1 invests k^*.[19] For small enough m or large enough H, an investment of k^* is no longer part of an equilibrium. Proposition 4 shows that Firm 1 responds to small m by investing more than k^* and responds to large H by investing less than k^*.

Proposition 4 *Suppose that for $m = 1$, $H = 0$ there is an even-share equilibrium in which Firm 1 invests $k^* > 0$ and earns strictly positive profits. Then,*

(i) There exists an $\hat{m}$ such that for all $m < \hat{m}$, every non-degenerate equilibrium involves an investment $k > k^*$ by Firm 1. Moreover there is a non-empty interval $(m', \hat{m})$ on which non-degenerate equilibria exist. For all $\hat{m} \leq m \leq 1$, an investment of k^* by Firm 1 remains part of an equilibrium.

(ii) There exists an $\hat{H}$ such that for all $H > \hat{H}$, every non-degenerate equilibrium involves an investment $k < k^*$ by Firm 1. Moreover there is a non-empty interval $\left(\hat{H}, H'\right)$ on which non-degenerate equilibria exist. For all $0 \leq H \leq \hat{H}$, an investment of k^* remains part of an equilibrium.

The more interesting part of Proposition 4 is part (i). The result that, as m falls, there may be more investment without patents relies crucially on the fact that increases in investment raise the probability of a successful innovation. This increase in probability raises the expected future returns to collusion without affecting the instantaneous gains from deviating after a successful innovation, thus making collusion easier. Formally, for $H = 0$ the conditions for an investment of k^* to be part of an even-share equilibrium are the following:

$$\frac{\pi_0}{m} \leq \frac{1}{n+1}\frac{\pi_0}{m} + \frac{1}{n+1}\frac{\delta}{1-\delta}mh(k^*)\frac{\pi_0}{m} \tag{5}$$

$$k^* < \frac{1}{n+1}\frac{\delta}{1-\delta}h(k^*)\pi_0 \tag{6}$$

When m decreases, the future expected profits on the equilibrium path, $\frac{1}{n+1}\frac{\delta}{1-\delta}mh(k^*)\frac{\pi_0}{m}$, are unaffected, but the temptation to deviate, $\frac{\pi_0}{m} - \frac{1}{n+1}\frac{\pi_0}{m}$, increases. For m low enough, condition (5) can no longer be satisfied. The solution is to raise investment, thereby increasing expected future collusive profits without affecting the temptation to deviate.

Suppose that, on the contrary, investment raised the return to a successful innovation without affecting its likelihood. That is, suppose we had $p = mh$, for some $h \leq 1$, and $\bar{\pi} = \frac{\pi(k)}{m}$, with $\pi'(k) > 0$. Then, increased investment would raise both the future returns to

[19] Some sufficient conditions are $\frac{\delta}{1-\delta}h'(0)\pi_0 > 1$, $n < \frac{\delta}{1-\delta}h(k^*)$, and $k^* < \frac{1}{n+1}\frac{\delta}{1-\delta}f(k^*)\pi_0$.

colluding and the instantaneous gains from deviating in offsetting fashion, so that increases in investment would not make collusion any easier (or more difficult).

In what follows, we describe an experiment that directly tests Proposition 4 by considering different treatments which vary the value of m.

4 Experimental Setup and Results

In this section, we present the design and results of a lab experiment tailored to achieve several goals. First, to test specifically some of the results of the theory, in particular the effect of increased riskiness described in Proposition 3 and the possibility of higher levels of investment described in Proposition 4. Second, since a degenerate equilibrium always exists, the experiment can also shed light on equilibrium selection issues and provide some empirical evidence on investment levels with and without legal protection.

4.1 Experimental setup

The experimental study is based on four different treatments. Two treatments correspond to an environment with a legal monopoly on the stochastic outcome of investments (we refer to those as patent treatments) and two to an environment with no legal protection (we refer to those as parasite treatments). Within each regime (patents vs parasites), we implement two different scenarios, corresponding to two different investment options described in Table 1. In one option, there are relatively high probabilities of obtaining a low prize; in the other option, the prize is doubled and the probabilities are halved. We refer to the four treatments as patent-low-prize, patent-high-prize, parasite-low-prize and parasite-high prize.

We reproduce infinitely repeated games in the lab using a standard procedure involving a random continuation rule (see Dal Bo and Frechette 2011, Dal Bo 2005 and Casari and Camera 2009 for recent examples). At the end of each round, the computer randomly determines whether or not another round will be played in the game. The probability of continuation is fixed at 0.85 for all treatments and is independent of any choices players make during the game. The players thus play a series of games of random length.

In the two patent treatments, all games are single-player games (there is no interaction with other players). In the first round of each game, the player first obtains an initial endowment of 11 tokens and makes an investment decision, choosing to invest 0, 1, 6 or 11 tokens. This initial investment determines the probability of obtaining a prize in each round of the game but has no influence on the other games. The exact probabilities and the level of the prize depend on the treatment as described in Table 1.

In the parasite treatments, each game involves two players. At the beginning of the game, each player receives 11 tokens and one of them is randomly selected to be the innovator (to avoid framing issues, in the instructions we call the innovator Role A and the imitator Role B.) In the first round, the innovator makes an investment decision with the same options as in the patent treatments (the parasite, takes no action in the first round). In the subsequent rounds, whenever the investment is successful (the probability of success is determined by the decision of the innovator in the first round), the two players play a prisoner's dilemma/pricing game represented in Table 2.[20] Each player chooses between H and L. If they make the same choice, they split either high or low profits. If they make different choices, the player that chooses L gets all the low profits, while the other player gets nothing. This is meant to represent product market competition between the innovator and the imitator, and is a special case of our theoretical model in which the collusive share of profits is restricted to $\alpha = \frac{1}{2}$. At the end of each round where an innovation was obtained, each player observes the other player's choice (H or L).

When a game (randomly) ends, a new one starts and is played in the same way. In the parasite treatments, players are randomly re-matched with a different player. This procedure makes it unlikely that the same pair will play together more than once. In any case, the game is played anonymously and players cannot identify their partner. For the parasite treatments (resp. patent), fifteen minutes (resp. ten minutes) after the start of the session, no new game starts but players finish the games they started.[21]

4.2 Theoretical predictions

Our model allows us to make clear theoretical predictions. First, in both patent treatments, the optimal choice of a risk-neutral player is an investment level of 1, although the level of expected profits does not vary vastly across the different positive choices (12.6 for an investment of 1, 12.1 for 6 and 11.6 for 11).[22]

In the case of the parasite-low-prize treatment, an investment of 1 in the first round remains part of an equilibrium whereas in the parasite-high-prize treatment it does not.

[20] In the patent treatments, whenever the investment is successful, the prize is obtained entirely by the single player. Nevertheless, to keep the two set of treatments symmetric, players in the patent treatment also have to choose whether they want to price high or low as in the parasites treatment. The choice low gives them a profit of zero, and the choice they have to make is thus obvious, but it preserves symmetry with the parasite treatments.

[21] We did not put a time constraint on the games already started but they never lasted more than a few minutes.

[22] While an investment of 1 is optimal for a risk-neutral money maximizer, subjects may have other motivations as well. For instance, they might get benefits from switching choice to break the tediousness of the task. In addition, there was some possible benefit to playing 0 in order to end the game sooner and proceed to the next game, as each game had a small fixed payment associated with it.

Examining the incentives of the players, brings out clearly the mechanism developed in the theory. In both parasite treatments, for an investment of 1, in the subgame following a successful innovation each player's continuation payoff is 6.8 if both of them play H for the rest of the game. However, in the low-prize treatment a player's instantaneous gain from deviating to L is only 4, while in the high-prize treatment it is 8, so that cooperation is possible only with a low prize.

Overall, in the low-prize game, all investment levels form part of an equilibrium; in the high-prize game, all investment levels other than 1 form part of an equilibrium. From the discussion above we have one *clear prediction that can be tested*:

- An investment of 1 is less likely in the parasite-high-prize treatment than in the parasite-low-prize treatment (special case of Proposition 4)

We can also test the consistency of the pricing behavior with the mechanism we propose:[23]

- Following an investment of 1 by the innovator, the parasite playing L is more likely in the parasite-high-prize treatment than in the parasite-low-prize treatment (special case of Proposition 3)
- The probability of observing H, H increases with the initial investment of the innovator

Finally, we can shed light on equilibrium selection issues and show evidence on the following questions:

- Is the zero investment degenerate equilibrium more common in the parasite treatments?
- Is there on average more or less investment with or without patents and within parasites with high or low prize?

4.3 Experimental results

The 10 experimental sessions (3 of each parasite treatments and 2 of each patent treatment) were run between March and May 2012 at Ecole Polytechnique in a dedicated experimental lab. A specific software was designed to run the experiment to be able to rematch players

[23] These are not strictly speaking predictions, but are natural consequences of the model. For instance, in the parasite-high-prize treatment, playing 1 is not an equilibrium, so interpreting what happens off the equilibrium path is not unambiguous. However, we know that in the subgame following an innovation, the parasite should play L

while others were finishing their game.[24] The participants were a mix of students and staff at the university. A total of 132 people participated in the experiment playing a total of 1756 games. The average earnings of players was 17.8 euros. At the end of the game, the participants were asked to fill in a survey that allowed us to control for gender and whether the participants were students. In the survey, we also introduced questions about individuals' risk attitudes (Dohmen et al 2005). Thus, in some specifications we can also control for subjects self-reported risk attitudes.[25] In all the regression analysis that follow, the standard errors are clustered at the session level (as in Dal Bo and Frechette 2011 for instance), to control for possible session effects that would introduce correlation in errors.[26]

4.3.1 Patents vs parasites

As we previously discussed, comparing the level of investment in innovation with and without legal protection based on real world data is hard for the simple reason that, since protection regimes uniformly apply to all those in the same industries, counter-factuals do not typically exist. Experiments creating artificial counter-factuals, are thus a valuable source of evidence to shed light on this comparison. As we can see in Figure 1, innovators invest on average very similar amounts in the patent and in the parasite treatments. The average investment is in fact slightly higher in the absence of patents, but this difference is not significant (p-value of 0.149 in a t-test and non significant coefficient in a regression controlling for individual characteristics).

These results thus undermine the idea that patent protection is unavoidable to encourage investments in innovation. This idea is often based on the presumption that, in the absence of legal protection, players would revert to the degenerate equilibrium where parasites act aggressively and the innovator thus refrains from investing. Table 4 reports the results of a regression where we test the effect of being in a patent treatment on the probability that the innovator invests zero. These results indicate that, contrary to the common wisdom, there is no significant difference in the frequency of zero investment between patents and parasite treatments. This evidence is in line with the motivation behind our theoretical model of

[24] The software was designed under a standard server/client architecture, the server uses' socket protocol to communicate with the clients. The server was implemented using the Adobe Flex technology and the clients deployed under Adobe Air. The backend of the server rely on relational database server (MySQL) for storing. Each "game" was considered as a thread, this method allowed us to resolve the main issue for rematching clients dynamically and keeping alive simultaneously other instances in progress.

[25] Some participants did not fill in the survey which explains that regressions controlling for individual characteristics will be run on fewer observations.

[26] We do not cluster at the individual level since the assumption in these type of environments is that each game can be considered as an individual observation. Note, however, that the significance of the main results is maintained if we do cluster at the individual level.

investment in the presence of rational parasites. The next step of our analysis is to test the main prediction of our theory.

4.3.2 Testing the central theoretical prediction

The main theoretical prediction is that we should observe innovators choosing a level of investment equal to 1 less often in the high-prize parasite treatments than in the low-prize parasite treatments. The theory does not, however, predict whether we should observe a reversal to the degenerate equilibrium or to a higher level of investment. The experimental evidence is then useful both to test the theoretical prediction and to shed light on equilibrium selection.

Figure 2 clearly shows that the difference between the low-prize and high-prize treatments is striking and goes in the direction suggested by the theory. Furthermore, Figure 3 suggests that learning strengthens this result. In the left panel we report the proportion of ones in the first game the players played and in the right the proportion in the later games. The proportion goes up for the low-prize treatments, while it slightly decreases in the high prize treatments. With learning players move closer to equilibrium behavior, although there is always a non-negligible fraction that play non-equilibrium strategies.

We test the central prediction controlling for different factors. Table 5 reports the results of a probit regression of the probability of an investment of one by the innovator. The probability of observing an investment of one in the low-prize-parasite treatment is significantly higher than in the high prize treatments. This result holds even when we control for individual characteristics and risk attitudes. A potential worry is that this result is not driven by our mechanism but by differences in the innovator's perceptions of the two gambles. However, when the same comparison is run between the two patent treatments, the effect tends to go in the other direction: Figure 4 shows that in the case of patents, an investment of one is more likely in the high-prize treatments.[27] Thus, if any behavioral mechanism not considered by our theoretical framework was playing a role this would tend to go in the opposite direction with respect to our findings.

It is clear that in the high prize treatment participants play 1 less often, but do they revert to not investing (the degenerate equilibrium)? In Figure 5, we present the full distribution of investment choices in the two parasite treatments. We see that there is both an increase in the frequency of zero investment and in the frequency of the maximum investment level. Importantly, average investment is 13% higher in the high-prize parasite treatment and this difference is significant (p-value of 0.03 in a t-test). Taking a mean-preserving spread of the distribution leads on average to more investment.

[27] A regression analysis confirms that the effect is significant.

4.3.3 Pricing behavior

The results of the previous section provide strong support for the central prediction of the theory. However to test further the coherence of our explanation, we examine in the current section the pricing behavior of the innovator and the parasite whenever a prize is obtained.

We first focus on the pricing behavior in games where the innovator invested 1 token. Figure 6 represents the distribution of outcomes in the prisoner's dilemma keeping in each game only the first round where a prize is obtained provided it exists (the plot averaging over all rounds looks very similar). We clearly see that the outcome LL where both players price low is much more likely in the high-prize treatment compared to the low-prize treatment as the theory suggested: the temptation to deviate is much larger.

It is, of course, not easy to interpret pricing behavior following an investment that should not occur in equilibrium. In particular, why would the innovator invest if he then expects LL to be the most probable outcome? It therefore seems more natural to focus exclusively on the behavior of the parasite following an investment of 1 by the innovator. The results presented in Figure 7 are even more striking: the parasite is much more likely to choose L in the high-prize treatment rather than the low prize treatments.[28]

The results presented in table 6 confirm the pattern observed in Figure 7. Even when controlling for individual characteristics, there is a significantly lower chance that the parasite plays L following an investment of 1 in the low-prize treatment.

A final test of coherence with the theory is to examine the pricing behavior by level of investment of the innovator. The more the innovator invests, the higher the expected continuation value in equilibrium if HH is played whenever a prize is obtained and thus the higher the incentives to keep cooperating (Table 3 shows how much the incentives to deviate decrease as the investment of the innovator increases). We thus plot in Figure 8 the pricing behavior of the parasite in the high-prize parasite treatments, separately for investments of 1, 6 and 11. There is a clear rise in the proportions of H's as the investment moves from 1 to 6, although no significant change as the investment goes from 6 to 11.

4.3.4 Discussion

Taken together, the results of the experiment provide evidence broadly coherent with our theoretical model. We show that the innovators are indeed less likely to choose the investment level of 1 in the high-prize parasite treatments and that if they do, parasites are more likely to price low (that is choose the action L in the prisoner dilemma game). Furthermore, the

[28]For Figure 6 and 7 and table 6, we keep in each game only the first round where a prize is obtained provided it exists.

overall results provide evidence that investment does not necessarily fall in the absence of a legal monopoly on the outcome of the investment. Indeed, on average investment in the parasite and patent treatments are quite similar. Thus, the experiment provides evidence that, at least in a controlled environment, a legal monopoly is not a necessary condition for investment and helps to shed some light on the basic intuitions underlying our theoretical model.

There are of course other theories that can explain why there might be similar levels of investment with and without patents. The most obvious would appear to be a story of reciprocity (e.g. Berg et al. 1995 and Fehr et al. 1997): If the innovator invests a lot, the parasite returns the favor by pricing high. It is then rational for the innovator to invest in the first place. However it is hard to see how such a theory would lead to a higher investment level under parasites[29] but more importantly it does not seem capable of explaining the different investment choices between the low-prize and high-prize parasite treatments, which are central to our argument. Finally the significantly lower probability that parasites choose not to cooperate (play L) following an investment of 1 in the low-prize treatment with respect to the high-prize treatment while consistent with our theoretical framework seems hard to reconcile with a reciprocity explanation. Indeed, since both the motivation and the overall expected stakes are comparable in the two treatments, we would not expect any difference in the behavior of reciprocal players in this case.

5 Conclusion

We have shown that when interactions between investors and parasites are repeated over time, positive investments can occur even in the absence of legal protection and, possibly even at a faster rate. Our model dispenses with first-mover advantages, lags, product differentiation, and other factors that may benefit the innovator or limit the scope for imitation. These elements could be incorporated and would tend to reinforce our conclusions. We have taken a three-pronged approach: i) empirical evidence (supplied by others), ii) a theoretical framework and iii) experimental evidence.

We started the paper with the evidence provided by Greif (1993) that trade between merchants and intermediaries located on the other side of the Mediterranean was rendered possible by informal institutions. Our model suggests an informal arrangement complementary to the one developed by Greif, and suggests, moreover, that trade might have been even more intense because of the absence of legal rules. Merchants needed to keep the promise

[29] One could always think of a story where the reciprocity occurs only for sufficiently high level of investments (strictly above 1) and could thus encourage higher investments by the innovator

of the future high to keep intermediaries cooperative. Interestingly, the model suggests that the merchants would not send bigger ships (which would leave the incentives to deviate unchanged) but more robust ones having higher chances of reaching their final destination.

6 Appendix

The rationing rule: In some period, let p_1 be the lowest price charged by any firm and M_1 be the set of firms charging this price, p_2 be the second lowest price charged by any firm and M_2 be the set of firms charging this price, etc...

If $D(p_1) \leq \sum_{i \in M_1} q_t^i$ then each firm $j \in M_1$ sells $\frac{q_t^j}{\sum_{i=1}^{n+1} q_t^i} D(p_1)$ and all other firms sell nothing.

If $D(p_1) > \sum_{i \in M_1} q_t^i$, then firm j sells q_t^j. Define $D^2(p_2) = D(p_2) - \sum_{i \in M_1} q_t^i$. If $D^2(p_2) \leq \sum_{i \in M_2} q_t^i$ then each firm $j \in M_2$ sells $\frac{q_t^j}{\sum_{i=1}^{n+1} q_t^i} D^2(p_t)$. If $D(p_2) > \sum_{i \in M_1} q_t^i$, then firm j sells q_t^j. Proceed inductively, first defining $D^3(p_3)$ and so forth...

Proof of Proposition 1. Without loss of generality, we can restrict our attention to equilibria in which, along the equilibrium path, firms $2, ..., n+1$ are treated identically (see footnote) and deviations are punished by a path where all firms get zero profits. A choice of k by Firm 1 forms part of a constant-share equilibrium if and only if there exists an α and function $f : R \to [0, 1]$, such that for every $\pi \in R_+$,

$$\pi f(\pi) \leq \frac{\alpha}{n} f(\pi) \pi + \sum_{t=1}^{\infty} \delta^t \int_0^{\infty} \frac{\alpha}{n} f(\pi) \pi dF(\pi, k), \tag{7}$$

$$\pi f(\pi) \leq (1-\alpha) f(\pi) \pi + \sum_{t=1}^{\infty} \delta^t \int_0^{\infty} ((1-\alpha) f(\pi) \pi dF(\pi, k)) \tag{8}$$

and

$$-k + \sum_{t=1}^{\infty} \delta^t \int_0^{\infty} \alpha f(\pi) \pi dF(\pi, k) \geq 0. \tag{9}$$

Combining (7) and (8), we have that along an equilibrium path, for all π

$$\pi f(\pi) \leq \frac{1}{n} \sum_{t=1}^{\infty} \delta^t \left(\int_0^{\infty} f(\pi) \pi dF(\pi, k) \right) \tag{10}$$

Since the right hand side of the above inequality is bounded by assumption, there is a maximum single period amount that the firms will be able to split along any equilibrium path. Denote this amount by $\widetilde{\pi}$ (thus, $\widetilde{\pi} = \max \pi f(\pi)$ such that (10) holds).

We can restrict ourselves to functions f with $f(\pi) = \frac{\widetilde{\pi}}{\pi}$ for $\pi > \widetilde{\pi}$, and $f(\pi) = 1$ for $\pi \leq \widetilde{\pi}$. To see this, suppose that we have an equilibrium where for some $\pi > \widetilde{\pi}$, $f(\pi) < \frac{\widetilde{\pi}}{\pi}$ and/or for some $\pi \leq \widetilde{\pi}$, $f(\pi) < 1$. Define f' to be equal to f, except that $f'(\pi) = \frac{\widetilde{\pi}}{\pi}$ for all $\pi > \widetilde{\pi}$ and $f' = 1$ for all $\pi \leq \widetilde{\pi}$,. Then $\pi f'(\pi) \left(1 - \frac{\alpha}{n}\right) \leq \widetilde{\pi} \left(1 - \frac{\alpha}{n}\right) \leq \sum_{t=1}^{\infty} \delta^t \int_0^{\infty} \frac{\alpha}{n} f(\pi) \pi dF(\pi, k) \leq \sum_{t=1}^{\infty} \delta^t \int_0^{\infty} \frac{\alpha}{n} f'(\pi) \pi dF(\pi, k)$, and similarly. $\pi f'(\pi)(\alpha) \leq$

$\sum_{t=1}^{\infty}\delta^t\int_0^{\infty}(1-\alpha)\,f'(\pi)\,\pi dF(\pi,k)$. Also, $-k+\sum_{t=1}^{\infty}\delta^t\int_0^{\infty}(1-\alpha)\,f'(\pi)\,\pi dF(\pi,k)\geq 0-k-\sum_{t=0}^{\infty}\delta^t c+\sum_{t=1}^{\infty}\delta^t\int_0^{\infty}(1-\alpha)\,f(\pi)\,\pi dF(\pi,k)\geq 0$. Thus, $f'(\pi)$ also yields an equilibrium.

Thus, a choice of k, forms part of an equilibrium if and only if there exists a $\widetilde{\pi}$ and α. ■

Proof of Proposition 2. Since $E(\pi|k)>0$, there is a $\bar{\pi}$ such that $\int_0^{\bar{\pi}}\pi dF(\pi,k)>0$. For an innovation worth $\pi\leq\bar{\pi}$, let $p(\pi)$ be the monopoly price; for an innovation worth $\pi>\bar{\pi}$ let $p_{\bar{\pi}}(\pi)<p(\pi)$ be a price that yields a total revenue of $\bar{\pi}$.

We find a $\bar{\delta}>0$ such that the following strategies form a subgame perfect equilibrium whenever $\delta\geq\bar{\delta}$.

- On the equilibrium path:
  - Firm 1 chooses $\bar{k}$ in period 0.
  - In period $t=1,...,$ if an innovation with monopoly profits $\pi\leq\bar{\pi}$ is obtained, each firm chooses $\left(p(\pi),\frac{1}{n+1}q(p(\pi))\right)$. If an innovation with monopoly profits $\pi>\bar{\pi}$ is obtained, each firm chooses $\left(p_{\bar{\pi}}(\pi),\frac{1}{n+1}q(p_{\bar{\pi}}(\pi))\right)$.
- If any firm has deviated from the above in some period $s<t$, then in period t all firms choose $(0,q(0))$.

We now establish that the above strategies form a subgame perfect equilibrium. If any firm has deviated in the past, the firms play a single-shot equilibrium thereafter, so we restrict our attention to subgames in which no firm has previously deviated.

Following a successful innovation, a firm's best deviation is to just undercut the other firms and choose a quantity at least as large as demand. For the strategies to form an equilibrium, the following must hold for all $\pi\leq\bar{\pi}$:

$$\pi\leq\frac{1}{n+1}\pi+\frac{\delta}{1-\delta}\frac{1}{n+1}\left(\int_0^{\bar{\pi}}\pi dF(\pi,k)+\widetilde{\pi}\left(1-F\left(\widetilde{\pi}\right)\right)\right)\tag{11}$$

There is a $\delta_1<1$ such that (11) holds for all $\pi\leq\bar{\pi}$ and $\delta\geq\delta_1$.

Now consider Firm 1's incentives to invest k in period 0. It's best deviation in period zero is not to invest. Thus for the strategies to form an equilibrium, firm 1's expected date zero profits must be positive:

$$-k+\frac{\delta}{1-\delta}\frac{1}{n+1}\left(\int_0^{\bar{\pi}}\pi dF(\pi,k)+\widetilde{\pi}\left(1-F\left(\widetilde{\pi}\right)\right)\right)\geq 0\tag{12}$$

There is a δ_2 such that (12) holds for all $\delta\geq\delta_2$.

Choosing $\bar{\delta} = \max(\delta_1, \delta_2)$ establishes the proposition. ■

Proof of Proposition 3. Conditions (1) and (2) can be rewritten as

$$\pi \leq \frac{\delta}{1-\delta}\frac{\alpha}{n-\alpha}\left(\int_0^{\widetilde{\pi}} \pi dF(\pi,k) + \widetilde{\pi}\left(1 - F\left(\widetilde{\pi}\right)\right)\right) \tag{13}$$

$$\pi \leq \frac{\delta}{1-\delta}\frac{1-\alpha}{\alpha}\left(\int_0^{\widetilde{\pi}} \pi dF(\pi,k) + \widetilde{\pi}\left(1 - F\left(\widetilde{\pi}\right)\right)\right) \tag{14}$$

Integrating by parts, we can express these conditions as:

$$\begin{aligned} \pi &\leq \frac{\delta}{1-\delta}\frac{\alpha}{n-\alpha}\left[\widetilde{\pi} - \int_0^{\widetilde{\pi}} F(\pi,k)d\pi\right] \\ \pi &\leq \frac{\delta}{1-\delta}\frac{1-\alpha}{\alpha}\left[\widetilde{\pi} - \int_0^{\widetilde{\pi}} F(\pi,k)d\pi\right] \end{aligned}$$

From the definition of second order stochastic dominance, if F second order stochastically dominates G, then

$$\left[\widetilde{\pi} - \int_0^{\widetilde{\pi}} G(\pi,k)d\pi\right] \leq \left[\widetilde{\pi} - \int_0^{\widetilde{\pi}} F(\pi,k)d\pi\right]$$

so that the constraints (13) and (14) are harder to satisfy under G than under F. Similarly, constraint (3) also becomes harder to satisfy. ■

Lemma 1 *Suppose that when Firm 1 invests k^*, in a subgame following the realization of an innovation, every equilibrium yields zero profits for all firms. Then the only possibility for a non-degenerate equilibrium involves Firm 1 investing more than k^*.*

Proof of Lemma 1. If every firm earns zero profits in any subgame following the realization of an innovation, it must be that even if all firms equally share profits ($\alpha = n/(n+1)$), splitting positive profits is not viable. That is,

$$\pi > \frac{1}{n+1}\pi + \frac{1}{n+1}\frac{\delta}{1-\delta}p\left(k^*\right)\pi$$

Only a choice of $k > k^*$ will increase the right hand side of the above inequality. ■

Lemma 2 *Suppose that when Firm 1 invests k^*, in a subgame following the realization of an innovation, there are equilibria in which firms earn positive profits, but none of these yield Firm 1 sufficient expected profits at date zero to warrant the initial investment of k^*. Then the only possibility for a non-degenerate equilibrium involves Firm 1 investing less than k^*.*

Proof of Lemma 2. Since there are continuation equilibria with positive profits, it must be that an even split of the innovation is a continuation equilibrium, since that is the easiest equilibrium to sustain in the subgame. Since Firm 1 does not invest k^* for any of these continuation equilibria, we have,

$$-k^* + \frac{1}{n+1}\frac{\delta}{1-\delta}p\left(k^*\right)\pi \; < 0. \tag{15}$$

For any k, let $(1-\alpha(k))$ be the smallest share for Firm 1 (if it exists) for which Firm 1 would be willing to invest k. That is,

$$\begin{aligned} k &= (1-\alpha(k))\frac{\delta}{1-\delta}p(k)\pi \text{ and} \\ \alpha(k) &= 1-\frac{k}{\frac{\delta}{1-\delta}p(k)\pi} \end{aligned}$$

From (15), $\alpha(k^*) < \frac{n}{n+1}$. Note that for $k > k^*$, $\alpha(k) < \alpha(k^*)$, since $\alpha(k)\frac{\delta}{1-\delta}p(k)\pi = \frac{\delta}{1-\delta}p(k)\pi - k \leq \frac{\delta}{1-\delta}p(k^*)\pi - k^* = \alpha(k^*)\frac{\delta}{1-\delta}p(k^*)\pi$, where the inequality follows from the fact that k^* maximizes $-k + \frac{\delta}{1-\delta}p(k)\pi$, and since p is increasing in k.

Since an investment of k^* by Firm 1 does not form part of an equilibrium, it must be that if Firms 2,...,n obtain a share $\frac{\alpha(k^*)}{n}$ of an innovation they will have an incentive to deviate. That is,

$$\begin{aligned} \pi &> \frac{\alpha(k^*)}{n}\pi + \frac{\alpha(k^*)}{n}\frac{\delta}{1-\delta}p(k^*)\pi \\ &= \frac{\alpha(k^*)}{n}\pi + \frac{1}{n}\left(\frac{\delta}{1-\delta}p(k^*)\pi - k^*\right) \end{aligned} \tag{16}$$

If a choice of $k > k^*$ by Firm 1 forms part of an equilibrium, then

$$\begin{aligned} \pi &\leq \frac{\alpha(k)}{n}\pi + \frac{\alpha(k)}{n}\frac{\delta}{1-\delta}p(k)\pi \\ &= \frac{\alpha(k)}{n}\pi + \frac{1}{n}\left(\frac{\delta}{1-\delta}p(k)\pi - k\right) \\ &\leq \frac{\alpha(k)}{n}\pi + \frac{1}{n}\left(\frac{\delta}{1-\delta}p(k^*)\pi - k^*\right) \end{aligned}$$

From (16) we have

$$\begin{aligned} \frac{\alpha(k^*)}{n}\pi + \frac{1}{n}\left(\frac{\delta}{1-\delta}p(k^*)\pi - k^*\right) &< \pi \leq \frac{\alpha(k)}{n}\pi + \frac{1}{n}\left(\frac{\delta}{1-\delta}p(k^*)\pi - k^*\right) \\ &\Rightarrow \alpha(k^*) < \alpha(k), \end{aligned}$$

a contradiction. Thus, all non-degenerate equilibria (if they exist), involve a choice of $k < k^*$ by Firm 1. ■

Proof of Proposition 4. (i) Under the conditions of the proposition, we have,

$$\frac{\pi_0}{m} \leq \frac{1}{n+1}\frac{\pi_0}{m} + \frac{1}{n+1}\frac{\delta}{1-\delta}mh(k^*)\frac{\pi_0}{m} \tag{17}$$

$$k^* < \frac{1}{n+1}\frac{\delta}{1-\delta}h(k^*)\pi_0 \tag{18}$$

when $m = 1$. Define $\widehat{m}$ as the value of m such that following an innovation, all players are indifferent between colluding and deviating:

$$\frac{\pi_0}{\widehat{m}} = \frac{1}{n+1}\frac{\pi_0}{\widehat{m}} + \frac{1}{n+1}\frac{\delta}{1-\delta}\widehat{m}h(k^*)\frac{\pi_0}{\widehat{m}}$$

$$\Leftrightarrow n = \frac{\delta}{1-\delta}\widehat{m}h(k^*)$$

For $m \geq \widehat{m}$, (17) holds so that Firm 1investing k^* still forms part of an equilibrium.

If $m < \widehat{m}$, collusion is no longer possible, even in the most favorable situation of an equal split of profits. From Lemma 1, the only possibility for a non-degenerate equilibrium involves an investment greater than k^*. We now show that there are such equilibria.

Define $k' > k^*$ by

$$k' = \frac{1}{n+1}\frac{\delta}{1-\delta}h(k')\pi_0$$

We have $n = \frac{\delta}{1-\delta}\widehat{m}h\left(k^*\right) < \frac{\delta}{1-\delta}\widehat{m}h\left(k'\right)$. Define $m' < \widehat{m}$ by

$$n = \frac{\delta}{1-\delta}m'h\left(k'\right)$$

For all $m' \leq m \leq m^*$ it is an equilibrium for Firm 1 to invest k and the firms to evenly split the profits from any innovation for some $k > k^*$ (in particular for $k = k'$).

(ii) First note that k^* maximizes $-k + \frac{\delta}{1-\delta}\pi_0 h(k)$ and thus satisfies

$$h'\left(k^*\right) = \frac{1}{\frac{\delta}{1-\delta}\pi_0} \tag{19}$$

By assumption, $k^* < \frac{1}{n+1}\frac{\delta}{1-\delta}h(k^*)\pi_0$. Define H_1 by $H_1 + k^* = \frac{1}{n+1}\frac{\delta}{1-\delta}h(k^*)\pi_0$. For $H > H_1$, an investment of k^* is sustainable only if Firm 1 obtains a share greater than $\frac{1}{n+1}$ of the profits from an innovation.

For any (H, k), let $(1 - \alpha\left(H, k\right))$ be the smallest share for which Firm 1 is willing to invest k. That is,

$$\begin{aligned}
H + k &= (1 - \alpha (H, k)) \frac{\delta}{1 - \delta} h(k) \pi_0 \\
\alpha (H, k) &= 1 - \frac{H + k}{\frac{\delta}{1-\delta} h(k) \pi_0} \qquad (20)
\end{aligned}$$

Note that α is decreasing in H. We have $\alpha (H_1, k^*) = \frac{n}{n+1}$ and $\alpha (H, k^*) < \frac{n}{n+1}$ for $H > H_1$.

For $H > H_1$, an investment of k^* by Firm 1 is sustainable if and only if, following an innovation, Firms 2,...,n will accept a share $\frac{\alpha(H,k^*)}{n}$. That is, if and only if

$$\begin{aligned}
\frac{\pi}{m} &\leq \frac{\alpha (H, k^*)}{n} \frac{\pi}{m} + \frac{\delta}{1 - \delta} \frac{\alpha (H, k^*)}{n} mh (k^*) \frac{\pi}{m} \\
n &\leq \alpha (H, k^*) + \frac{\delta}{1 - \delta} \alpha (H, k^*) mh (k^*) \qquad (21)
\end{aligned}$$

Given H and K, let

$$d (H, k) = \alpha (H, k) + \frac{\delta}{1 - \delta} \alpha (H, k) mh (k) ,$$

so that (21) can be written as $n \leq d (H, k^*)$. By assumption, $n < d (H_1, k^*)$.

Note that d is decreasing in H. Define $H_2 > H_1$ by $n = d (H_2, k^*)$. For $H \leq H_2$ an investment of k^* by Firm 1 forms part of an equilibrium since $n \leq d (H, k^*)$. For $H > H_2$, an investment of k^* by Firm 1 is not sustainable. By Lemma 2, the only possibility for a non-degenerate equilibrium involves a smaller choice of k by Firm 1. We now show that a choice of $k < k^*$ will be sustainable over some range.

We have

$$\begin{aligned}
\frac{\partial d (H_2, k^*)}{\partial k} &= \frac{\partial \alpha (H_2, k^*)}{\partial k} + \frac{\delta}{1 - \delta} m \left(\frac{\partial \alpha (H_2, k^*)}{\partial k} h (k^*) + \alpha (H_2, k^*) h' (k^*) \right) \\
&= \frac{\partial \alpha (H_2, k^*)}{\partial k} + \frac{\delta}{1 - \delta} m \left(\frac{\partial \alpha (H_2, k^*)}{\partial k} h (k^*) + \alpha (H_2, k^*) \frac{1}{\frac{\delta}{1-\delta} \pi_0} \right)
\end{aligned}$$

Differentiating (20) yields

$$\frac{\partial \alpha}{\partial k} = - \frac{1}{\frac{\delta}{1-\delta} \pi_0} \frac{(h (k) - h' (k) (H + k))}{h (k)^2}$$

Thus,

$$\begin{aligned}\frac{\partial d\left(H_2,k^*\right)}{\partial k} &= \frac{\partial \alpha\left(H_2,k^*\right)}{\partial k}-\frac{1}{\pi_0}m\frac{\left(h\left(k^*\right)-h'\left(k^*\right)\left(H_2+k\right)\right)}{h\left(k^*\right)}+\frac{1}{\pi_0}m\alpha\left(H_2,k^*\right)\\ &= \frac{\partial \alpha\left(H_2,k^*\right)}{\partial k}<0,\end{aligned}$$

where the inequality follows from the fact that $\frac{\partial \alpha(H_2,k^*)}{\partial k}$ has the same sign as $-\left(\frac{\delta}{1-\delta}\pi_0 h\left(k^*\right)-\left(H_2-k^*\right)\right)$, and $\frac{\delta}{1-\delta}\pi_0 h\left(k^*\right)-\left(H_2-k^*\right)>0$ as Firm 1 is willing to invest k^* when $H=H_2$.

Since $\frac{\partial d(H_2,k^*)}{\partial k}<0$, and all our functions are continuous, a choice of k below k^* is sustainable for some $H>H_2$. ■

Table 1: **Investment options in high vs low prize treatments**

	Low-prize	**treatments**	**High-prize**	**treatments**
Investment	Prize	Probability	Prize	Probability
0	8	0	16	0
1	8	0.3	16	0.15
6	8	0.4	16	0.2
11	8	0.5	16	0.25

Table 2: Prisoner's dilemma between innovator and parasite

	H	L
H	$\Pi/2, \Pi/2$	$0, \Pi$
L	$\Pi, 0$	$0, 0$

Note: $\Pi = 8$ for the low-prize treatments and $\Pi = 16$ for the high-prize treatments

Table 3: Profits and deviation incentives in parasite treatments

	Low-prize	**treatments**	**High-prize**	**treatments**
Investment	Expected profits of the innovator	Deviation incentive	Expected profits of the innovator	Deviation incentives
1	10.8	-2.8	14.8	1.2
6	13.1	-5.1	17.1	-1.1
11	15.3	-7.3	19.3	-3.3

NOTE: Expected profits of innovator calculated under the assumption that (H, H) is played whenever a prize is obtained. Deviation incentives is the difference between the prize (i.e deviation profits) and the expected profits if (H, H) is played whenever a prize is obtained (i.e expected profits on equilibrium path). A positive value for the deviation incentives means that level of investment cannot be part of an equilibrium.

Table 4: Probability of observing no investment by the innovator

	(1)	(2)	(3)
Patent treatment	.57	.52	.16
	(.50)	(.40)	(.60)
Individual controls (except risk)	no	yes	yes
All controls	no	no	yes
Number of observations	1756	1702	1692

NOTE: Standard errors clustered at the session level in parentheses. ***Significant at the 1 percent level, **Significant at the 5 percent level , *Significant at the 10 percent level

Table 5: Probability of observing investment of 1 by the innovator

	(1)	(2)	(3)
Low prize treatment	.37**	.29**	.37*
	(.15)	(.13)	(.21)
Individual controls (except risk)	no	yes	yes
All controls	no	no	yes
Number of observations	947	893	893

NOTE: Standard errors clustered at the session level in parentheses . ***Significant at the 1 percent level, **Significant at the 5 percent level , *Significant at the 10 percent level

Table 6: Probability of parasite playing L in games where innovator invested 1

	(1)	(2)	(3)
Low prize treatment	-.44	-.36	-.71**
	(.38)	(.31)	(.36)
Individual controls (except risk)	no	yes	yes
All controls	no	no	yes
Clustered standard errors	no	no	no
Number of observations	183	171	167

NOTE: We keep only observations corresponding to the first time a prize is obtained in the game (provided it exists). Standard errors clustered at the session level in parentheses. ***Significant at the 1 percent level, **Significant at the 5 percent level , *Significant at the 10 percent level

Figure 1: Comparing investment levels

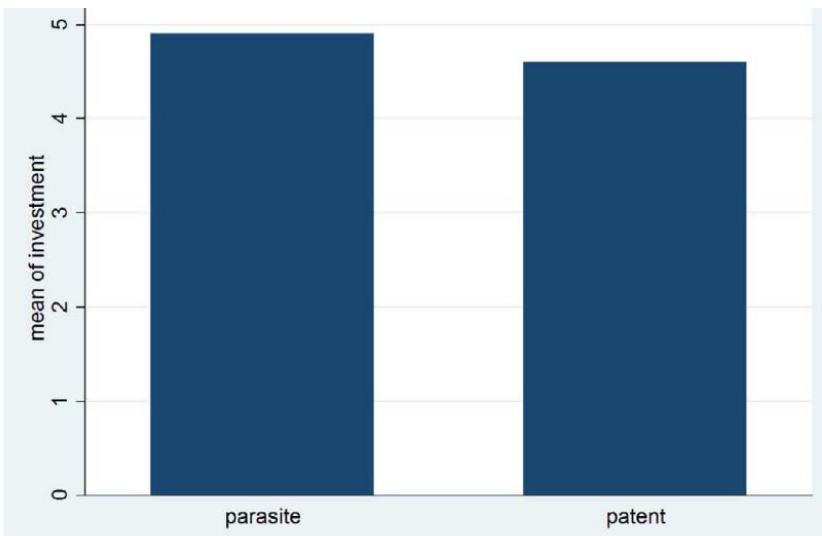

Figure 2: Investment of one by treatment

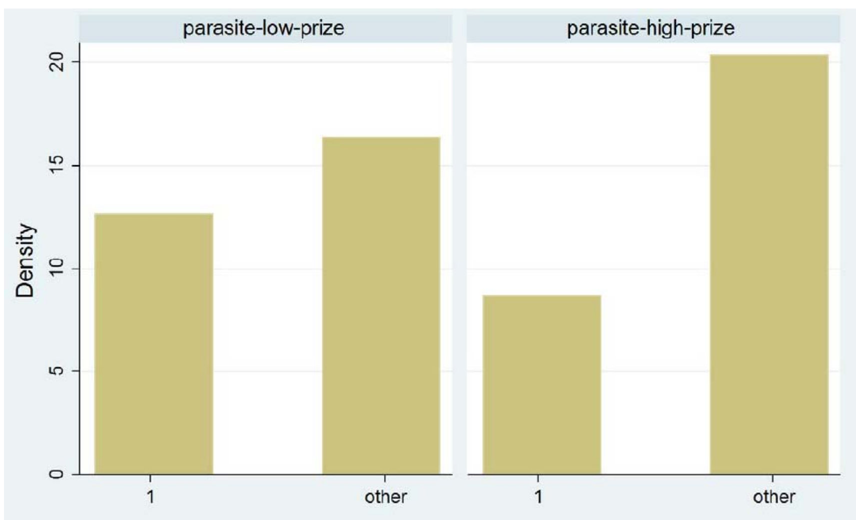

Figure 3: Investment of one: early vs later rounds

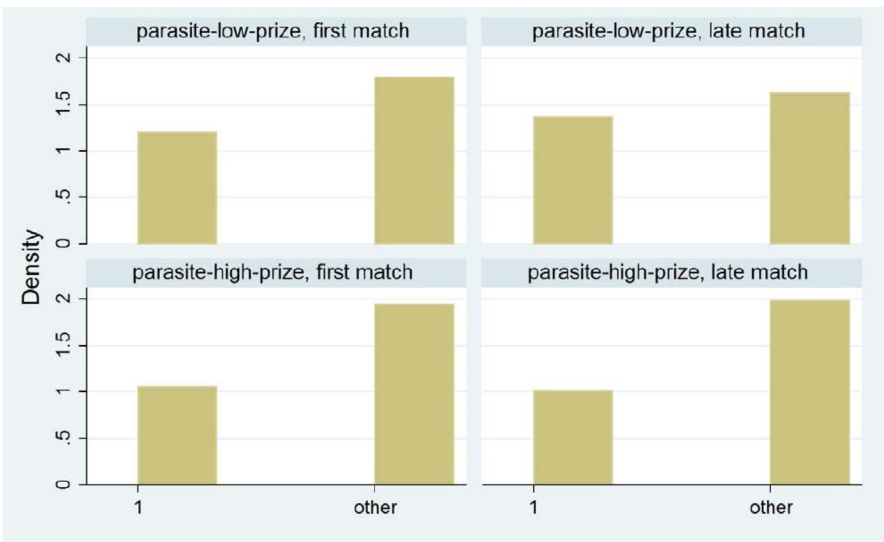

Figure 4: Investment of one: patents vs parasites

Figure 5: Investment choices by parasite treatment

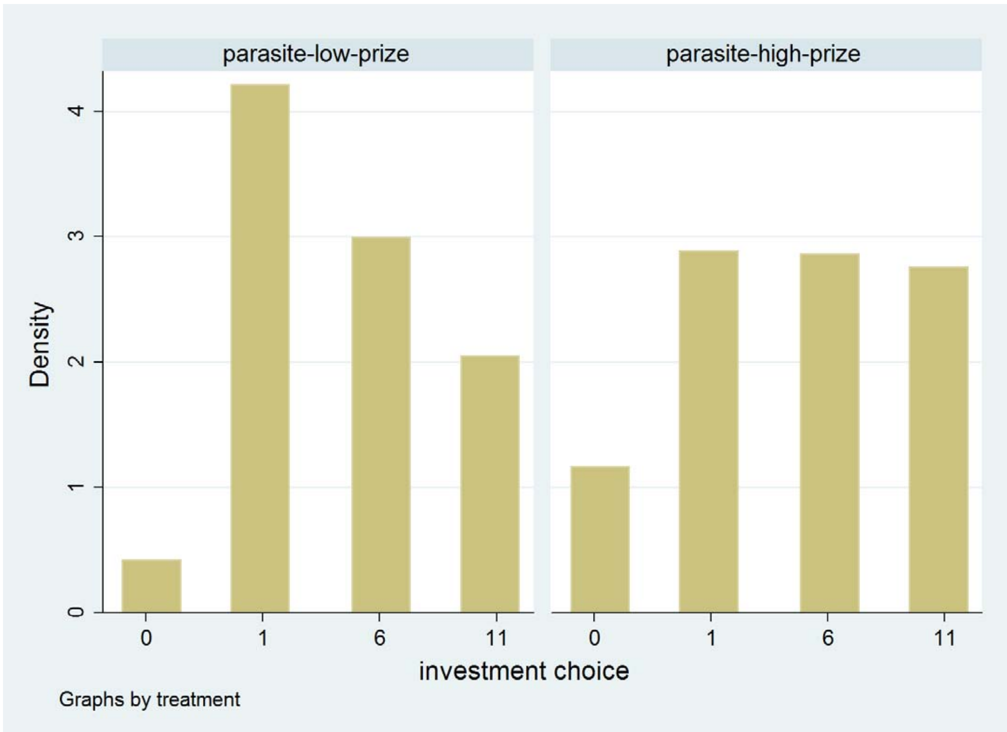

Figure 6: Pricing behavior following investment of 1

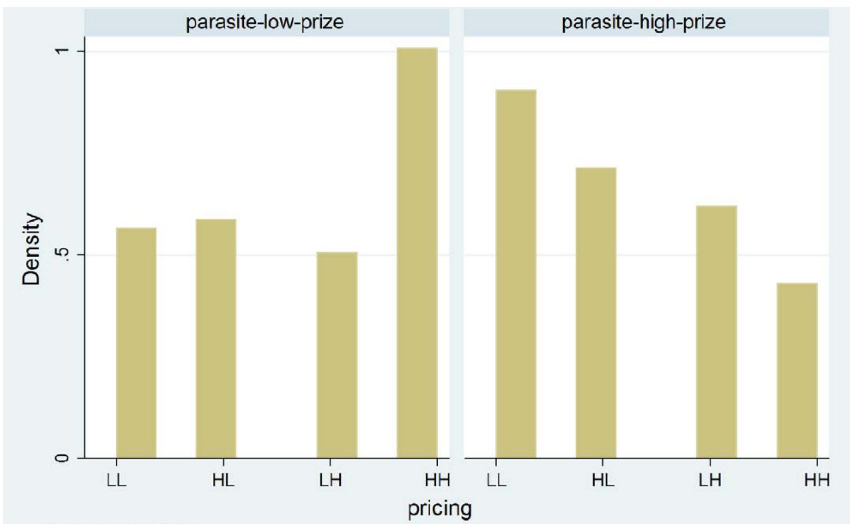

Figure 7: Pricing behavior of parasite following investment of 1

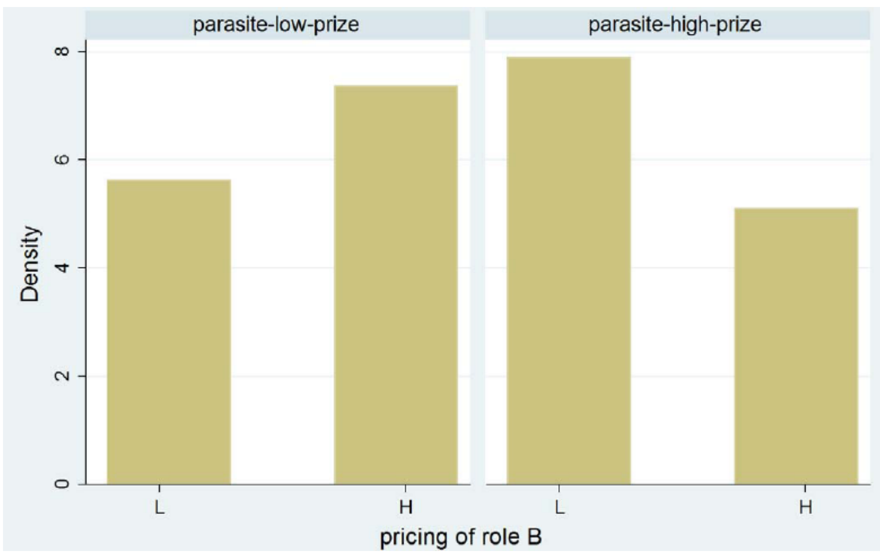

Figure 8: Pricing behavior by level of investment

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