Less Protection, More Innovation?*

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Abstract

Reward theory, which represents the conventional economic view, suggests that the optimal strength of patents depends on a use-creation tradeoff; the inevitable production of dead-weight losses in the ex post market for the invention for the purpose of fostering technological progress. This paper demonstrates a caveat in this approach by using game theory. Strong patents increase the value of becoming an inventor. As such, more firms are attracted to R&D. However, each firm rationally discounts the probability that it will be the first to obtain a patent, and may therefore reduce or abandon its R&D investment. This leads to a lower invention probability per R&D firm, which in turn may lead to a lower aggregate invention probability. In such cases, weaker patent protections can simultaneously foster innovation and eliminate dead-weight losses in the ex post market for the invention. Hence, contrary to the conventional view, the use-creation tradeoff does not exist globally.

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"Nobody goes there anymore... It's too crowded."
-Yogi Berra

I. Introduction

Reward theory "views ... the patent system as a device that enables an inventor to capture the returns from his investment in the invention" (Kitch (1977), p. 266).[1] This theory embodies the conventional view of the patent system,[2] and suggests, absent patents, inventors' incentive to invent would be low, which would retard technological progress. The basic function of patents is to allow patentees to prevent others from legally making, using or selling the invented product. The primary negative effect of the patent system on consumer welfare flows from such prevention, since it generates a concentrated market for the invented product.

The necessity of sacrificing social gains in the product market to increase technological progress can conveniently be called the *use-creation tradeoff*.[3] This tradeoff is the focal point of many articles discussing potential patent law reforms.[4] For example, a new and expanding branch of literature discusses the possibility of reforming patent law by making patent protections weaker. This can be achieved by allowing independent inventors (Maurer and Scotchmer (2002), Vermont (2006), Lemley (2007), Mungan (2011)), prior users (Shapiro (2006)), or secondary inventors (Henry (2010)) to make, use or sell a product which falls under the scope of the primary inventor's patent.[5] Alternative ways to reduce protections offered by patents include narrowing their scopes by making the patent breadth narrower and/or making the patent length shorter (Gilbert and Shapiro (1990)).[6] Yet another way to affect the use-creation tradeoff is by probabilisticly enforcing patentee's rights to exclude (Lemley and Shapiro (2005)).[7]

The conventional view of patents suggests that reducing patent protections through one of these methods lowers the expected return to being a patentee and therefore retards technological progress. The gains, on the other hand, is the elimination of deadweight losses in the ex-post product market. In what follows, I will refer to any patent regime which provides reduced patent protections as a *weak* patent regime.[8]

[1] *See also* Landes and Posner (2003) p. 294, where the authors refer to this explanation for the existence of patent law as the *standard rationale of patent law. But see* Lemley (2011) criticizing this and alternative theories (commercialization theory and prospect theory) of patent law.

[2] *See* Kitch (1977) at 266 (referring to the reward theory as "[t]he conventional view of the patent system"); Lemley (2011) at p. 55 (describing the reward theory as "the orthodox utilitarian theory of patent law" and suggesting that "[w]e grant patents, on this theory, to encourage inventions we wouldn't otherwise get."); Fisher (2001) at p. 178 (referring to the reward theory as the *incentive theory* and stating that this is "[t]he first and most common" Utilitarian approach to studying the patent system).

[3] Burtis and Kobayashi (2001) use the same phrase to refer to this tradeoff. Variants of this tradeoff have been identified, among others, by Nordhaus (1969), and are occasionally called the Nordhaus tradeoff. *See, e.g.* Denicolo and Franzoni (2004 p. 519).

[4] Reforms introduced through the *Leahy-Smith America Invents Act* act were *potential reforms* at the time the papers referenced in this article were written. This Act makes changes to the prior user rights defense, and therefore papers discussing the desirability of these rights, *e.g.* Shapiro (2006), can be classified as discussing the desirability of *actual* patent law reforms.

[5] *See also* DeNicolo and Franzoni (2004), La Manna, Macleod and de Meza (1989), Shapiro (2007) and Vermont (2007).

[6] *See also* Klemperer (1990) and Waterson (1990) analyzing patent breadth.

[7] *See also* Farrell and Shapiro (2008) at p. 1347 (analyzing the "welfare effects of probabilistic patents that are licensed without full determination of validity.")

[8] This definition may seem unnecessary, however, in the literature (*e.g.* as in Farrell and Shapiro (2008)) weak patents may refer exclusively to probabilistic patents and not include other methods of reducing expected returns to researchers.

Recently, this conventional view has been challenged by theoretical as well as empirical studies. Although empirical studies are few[9], there are articles which suggest that, unlike commonly believed, strengthening patents may not always foster innovation.[10] The theoretical literature, on the other hand, proposes that weak patents may mitigate patent hold-up problems, which likely occur when innovation is viewed as a cumulative process, and that therefore the effect of patent strength on innovation is ambiguous.[11] In a non-cumulative innovation context, however, theoretical literature suggests that "a generalized increase in patent breadth or scope, holding all else equal, unambiguously increases the innovation rate, because it does not affect the incentives of subsequent potentially infringing inventors." (Jaffe (2000), p. 545).

In this paper I show that strong patents may retard technological progress even in a non-cumulative innovation setting. In particular, I argue that when patent strength's effects on the number of potential inventors are considered, it follows that weakening patent protections may actually *contribute* to technological progress. To describe the logic behind this assertion, it is best to consider the intuition behind most existing articles analyzing weak patents in a non-cumulative innovation setting.

Generally, patents are considered as rewards which incentivize potential inventors to invest in research and development (R&D). The idea is simple – if inventors are offered substantial protections through patent law, they will be able to collect high profits from the invented product's market. Hence, firms increase their efforts to invent, and to collect higher profits, when they are offered protections through patent law. Increased efforts lead to a higher likelihood of invention, which implies greater technological progress.

Based on this reasoning, scholars conclude that greater patent protections should generate more innovation.[12] Although the standard reasoning highlights an important point, it fails to capture its secondary implication. When the value of becoming an inventor is increased, this option is more valuable for all firms who are potential inventors. Hence, when patents are strengthened, R&D becomes an attractive option for a greater number of firms. On the other hand, a secondary implication is that if a firm anticipates that more firms will conduct research, it may reduce or abandon its efforts fearing that it may be technologically inferior to its rivals,[13] and that it would end up incurring costs to invent a product which would be patented by a rival firm. In short,

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[9] *See*, Jaffe (2000), which includes a survey of the economic literature analyzing patent reforms, stating the problems associated with conducting empirical studies in this area: "There has been relatively little analysis of the effects of different degrees of patent scope. Such studies are very hard to do, because it is very difficult to measure patent scope in a systematic way across large numbers of patents, and because there are very few natural experiments in which different degrees of patent scope can be observed."

[10] *See, e.g.,* Kortum and Lerner (1999), Sakakibara and Branstetter (2001), Merges and Nelson (1990), Bessen and Hunt (2007), and Allred and Park (2007).

[11] *See* Scotchmer (1991) proposing the *cumulative innovation* framework, and Gallini (2002) suggesting that broad patents may lead to hold-up problems in this setting. *See also* Jaffe (2000) sub-sections 3.4.1.1.-3. for an excellent review of articles addressing this issue.

[12] *See, e.g.*, Proposition 1 in Henry (2010) at p. 6. where the author proves this result under a general set of assumptions. A similar result is achieved in La Manna, Macleod and de Meza (1989) Proposition 3 at p. 1435, since a strong patent regime "sustains more firms than a permissive regime". Shapiro (2006) also achieves this result, because stronger prior user rights decrease the equilibrium probability of innovation of R&D firms. Mungan (2011) derives this result under complete information in Proposition 1 at pp. 8-9, and under incomplete information in Corollary 1 at p. 13. Maurer and Scotchmer (2002) come to the same conclusion (as pointed out in Henry (2010) at p.6 note 7).

[13] Phenomena similar to abandoning R&D projects have been analyzed in earlier work. *See, e.g.*, Lippman and McCardle (1987) (analyzing 'dropout behaviour in R&D races') ; Fudenberg and Tirole (1986) (analyzing exits in dupoloies). But, to the best of my knowledge, the literature has not yet formalized the idea that such behavior may lead strong patents to retard innovation.

stronger patents may result in a greater number of firms engaging in initial R&D efforts, but a lower level of average R&D effort. This may, under certain circumstances, retard technological progress by decreasing the level of innovation.

To the best of my knowledge, this relatively intuitive idea has not been presented in the existing literature. There are numerous articles analyzing patent races,[14] and some have even formalized the idea that R&D firms may *dropout* of R&D races (Lippman and McCardle (1987)), which corresponds to *abandoning* an R&D project in the instant article. However, I am unaware of any previous work formalizing the fact that strengthining patent protections may retard technological progress by incentivizing firms to reduce R&D investments or to abandon their projects. I believe the main reason is that scholars have either ignored the effects of various patent regimes on the number of potential inventors, or assume that R&D leads to invention with certainty.[15]

In this article I formalize the idea that more protection can lead to less innovation by considering game theoretical models. I show that results are general, in that they can be obtained for weaker patents formed by allowing independent invention or prior user rights as a defense, as well as for those formed by probabilistic patents or patents with a narrower scope. I also show that conclusions are preserved in an incomplete information setting where R&D firms may be heterogenous in their R&D technologies. Finally, results are robust to the game solution concept. They follow under pure as well as mixed strategy equilibria, implying that results are not the product of assuming away coordination problems.

In deriving these results, I focus exclusively on the reward theory of patents. As such, I abstract from many issues previously identified by the *prospect theory* of patents,[16] which "conceives of the process of technological innovation as one in which resources are brought to bear upon an array of prospects, [i.e.] opportunit[ies] to develop a known technological possibility." (Kitch (1977), p. 266).[17] Under prospect theory, "granting to the developer of a pioneering invention an expansive set of entitlements ... enabl[es] him or her to coordinate research and development dedicated to improving the invention, thus reducing the dissipation of rents at the secondary level" (Fisher (2001), p. 182). By abstracting from issues identified in prospect theory, my goal is not only to point out an internal inconsistency in reward theory, but also to isolate a potential negative incentive effect of strong patents that does not depend on *secondary level* effects. This retardation effect was unnoticed in the reward theory literature so far, and may be of particular importance in discussing issues related to prior user rights and the social desirability of independent invention as a defense

[14] *See, e.g.,* Fudenberg, Gilbert, Stiglitz, and Tirole (1983), and Lipman and McCardle (1987). *See also* Barzel (1968).

[15] *See*, for instance, Mungan (2011) ignoring the effect of patent regimes on the number of R&D firms, and Maurer and Scotchmer (2002) assuming that invention occurs with certainty.

[16] I am also abstracting from issues identified in the commercializtion theory of patents, *see* Kieff (2001) and Abramowicz (2007). However, the main results in this article can be extended to a model which incorporates features of commercialization theory. This theory suggests that weak patents reduce R&D firms' incentives to commercialize their inventions once they invent them. These incentive effects can be incorporated into the current model by assuming that weak patents distort R&D firms ex ante incentives to invent due to reduced ex post expected profits. This would correspond to multiplying $\beta(W)$ and $\gamma(W)$ for all $W \in \{N, P\}$, as defined in (2) below, by a discount factor throughout this article.

[17] *See also* Grady and Alexander (1992) and Merges and Nelson (1990). The early literature focusing on prospect theory appears to be primarily concerned with "mitigat[ing] rent dissipation", "reduc[ing] the risk of duplicative activity" and "avoiding redundant inventive activity" (Fisher (2001) pp 182-3). As such, the early literature seems to be concerned with minimizing *creation costs* to address the use-creation tradeoff. The instant article, to the contrary, demonstrates that the use-creation tradeoff need not globally exist to begin with. More recent literature, focusing on the cumulative nature of innovation processes can be thought of as applying prospect theory through modern economics. *See supra* note 11 for articles focusing on cumulative R&D processes.

given recent reforms in patent law.[18] As such, the instant article may be of particular interest to empirical scholars, who may succeed in identifying conditions under which the proposed retardation effect is observed and the frequency with which such conditions arise.

In the remaining portions of this paper, I investigate the effect of patent strength on R&D activity in a game theoretical framework. In Section II, I consider a model of full information where the number of R&D firms are fixed, and show that technological progress is unambiguously increasing in R&D. Then, in Section III, I show that if the number of R&D firms is endogenously determined, stronger patents may actually retard technological progress. Section IV demonstrates that results are preserved under an incomplete information framework. It also shows that to incorporate the realistic possibility that firms may abandon R&D projects for which they have made some investments, it is sufficient to incorporate heterogeneity in R&D technologies across firms. Section V concludes.

II. Identical R&D Firms with Full Information

In this section, I analyze a simple model similar to that presented in Shapiro (2006).[19] As in Shapiro (2006), for simplicity, consider two identical R&D firms, which may invent a product if they invest in research. The analysis is qualitatively similar when N firms are present, but is lengthier and requires more complicated notation. Firms' probabilities of success depend on how much they invest in research. Formally, let $p_i = p(c_i)$ and $c_i \in [0, \infty)$ denote respectively firm i's probability of inventing the product, and its investment, where p satisfies the Inada conditions. A firm's expected pay-off is a function of its and its rival's investment decision, as well as the legal regime.

I will consider three legal regimes: (i) a strong patent regime (SPR), (ii) a permissive patent regime (PPR), and (iii) a patent regime with a narrow scope (NSPR). SPR, is a benchmark regime where all issued patents are valid, and the patentee has the right to exclude all other parties from making, using, or selling its invention. PPR is a regime where all patents are valid, but they may not be enforced to exclude independent inventors from making, using or selling the invention.[20] Finally, NSPR is a regime in which either patents have shorter lengths/narrower breadths (compared to an SPR), or where only a proportion of issued patents are valid.[21] I will refer to PPR and NSPR collectively as *weak* patent regimes.

Under SPR, if both firms are successful after research, they are equally likely to be rewarded the patent (equivalently to be the one to finish first), which grants a payoff of π_m. The firm who fails to obtain a patent gets a pay-off of zero. Similarly, under NSPR, if both firms are successful, one is randomly assigned the patent. What distinguishes NSPR from SPR, is the expected pay-off to the patentee, which is denoted as $\delta\pi_m$ with $\delta < 1$. δ reflects the discount associated with either a shorter patent length, narrower patent breadth, probabilistic enforcement of patents, or any combination of these three. On the other hand, in PPR if both firms are successful, both are entitled to profits

[18] *See, e.g.,* the Leahy-Smith America Invents Act.
[19] Shapiro (2006), Section 1, pp. 93-94.
[20] A patent regime allowing prior user rights as defined in Shapiro (2006), or a regime where independent invention is a defense to patent infringement as in Vermont (2006) and Mungan (2011), or runner up patents as defined in Henry (2010) are variants of a PPR.
[21] Probabilistic patents as defined in Farrell and Shapiro (2008) would fall under this category.

from the market, namely π_d.[22] I assume that $\frac{1}{2}\pi_m > \pi_d$.[23]

Given these definitions, a firm's expected pay-off can conveniently be expressed as a function of its and its rival's investment decisions, and the legal regime (L):

$$u_i = p_i(c_i)(1 - p_j(c_j))\beta(L)\pi_m + p_i(c_i)p_j(c_j)\gamma(L) - c_i \tag{1}$$

where

$$\beta(L) = \begin{cases} 1 \text{ if } L \in \{S, P\} \\ \delta \text{ if } L = N \end{cases} \tag{2}$$

and

$$\gamma(L) = \begin{cases} \frac{\pi_m}{2} \text{ if } L = S \\ \pi_d \text{ if } L = P \\ \frac{\delta\pi_m}{2} \text{ if } L = N \end{cases} \tag{3}$$

where S, P, and N respectively denote SPR, PPR, and NSPR. Given this notation, player i's best response (c_i^b) as a function of player j's investment (c_j) and the legal regime (L) can implicitly be expressed by the following first order condition:

$$p_i'(c_i^b) = \frac{1}{\beta(L)\pi_m - p_j(c_j)(\beta(L)\pi_m - \gamma(L))} \tag{4}$$

This implies that each player's strategy (c^*) in the pure strategy symmetric Nash Equilibrium is given by:

$$p'(c^*) = \frac{1}{\beta(L)\pi_m - p(c^*)(\beta(L)\pi_m - \gamma(L))} \tag{5}$$

The existence and uniqueness of a symmetric equilibrium is guaranteed by the fact that p satisfies the Inada conditions. A simple application of the intermediate value theorem should verify this claim. The left hand side (LHS) of eqn. (5) is greater than the right hand side (RHS) as c approaches 0, and the opposite holds for some large c since $\lim_{c\to\infty} p'(c) = 0$ and the RHS of eqn. (5) approaches $\frac{1}{\gamma(L)} > 0$ as c approaches infinity. This verifies that there is a symmetric equilibrium. That this equilibrium is unique is verified by the fact that the LHS is decreasing in c whereas the RHS is increasing. Having shown that there is a unique symmetric equilibrium, we can now demonstrate the well established fact in the previous literature that weaker patents retard technological progress in a non-cumulative innovation setting with a fixed number of R&D firms.

Proposition 1: *Invention occurs less frequently under weak patents.*

Proof: *Eqn. (5) implicitly defines the equilibrium investment $c^*(L)$. Applying the implicit function theorem reveals that:*

$$\frac{\partial c^*}{\partial \beta} = -\frac{\frac{\pi_m(1-p(c^*))}{(\beta\pi_m - p(c^*)(\beta\pi_m-\gamma))^2}}{p''(c^*) - \frac{p'(c^*)(\beta\pi_m-\gamma)}{(\beta\pi_m-p(c^*)(\beta\pi_m-\gamma))^2}} =$$

[22] Conclusions would not change if the first and second firms were entitled to $\pi_1 > \pi_2$ respectively. In this case, π_d would be the expected profits of a firm, which would be obtained by calculating a weighted average of π_1 and π_2.

[23] The first inequality would follow in any reasonable model. If $(1/2)\pi_m < \pi_d$, then the single patent holder under SPR can improve his profits by creating a subsidiary and giving him rights which would be conferred to an independent inventor in PPR.

$$-\frac{\pi_m(1-p(c^*))}{p''(c^*)(\beta\pi_m - p(c^*)(\beta\pi_m-\gamma))^2 - p'(c^*)(\beta\pi_m-\gamma)} = \tag{P.1.}$$

$$-\frac{(+)}{(-)-(+)} = (+)$$

and

$$\frac{\partial c^*}{\partial \gamma} = -\frac{\frac{p(c^*)\gamma}{(\beta\pi_m - p(c^*)(\beta\pi_m-\gamma))^2}}{p''(c^*) - \frac{p'(c^*)(\beta\pi_m-\gamma)}{(\beta\pi_m-p(c^*)(\beta\pi_m-\gamma))^2}} =$$

$$-\frac{p(c^*)\gamma}{p''(c^*)(\beta\pi_m - p(c^*)(\beta\pi_m-\gamma))^2 - p'(c^*)(\beta\pi_m-\gamma)} = \tag{P.2.}$$

$$-\frac{(+)}{(-)-(+)} = (+)$$

Next, note that

$$\beta(S) = \beta(P) = 1 \text{ and } \gamma(S) = \frac{\pi_m}{2} > \gamma(P) = \pi_d \tag{P.3.}$$

and

$$\beta(S) = 1 > \beta(N) = \delta \text{ and } \gamma(S) = \frac{\pi_m}{2} > \gamma(N) = \frac{\delta\pi_m}{2} \tag{P.4.}$$

implying together with (P.1) and (P.2.) that $p(c^*(S)) > p(c^*(P)),p(c^*(N))$, *which trivially implies that the probability of invention is smaller under weak patent regimes. Q.E.D.*

Proposition 1 demonstrates that weaker patents unambiguously retard technological innovation when there is a fixed number of R&D firms. The main claim of this paper, namely that weaker patents may foster technological progress when the number of R&D firms are determined endogenously, is demonstrated in the next section.

III. Endogenous Number of Firms with Full Information

To endogenize the number of R&D firms conducting research, consider the following adjustment to the model presented in the previous section. $\overline{E}$ firms decide whether or not to invest a small amount of F to purchase the necessary facilities to conduct R&D. $E \leq \overline{E}$ firms that make such investments, then decide how much to invest in increasing the probability with which they invent the product. As in the previous section, firm i's variable investment is denoted as c_i and produces a probability of $p_i = p(c_i)$ of invention.

Accordingly, to formalize the interactions between R&D firms, it is convenient to use a two-period game. In the first period, $\overline{E}$ firms decide whether or not to enter the R&D market. In the second period, $E \leq \overline{E}$ entrants choose their research investments (c). To reflect the fact that the number of entrants depend on the patent regime, let $E = E(L)$. Where $L \in \{S, N, P\}$ denotes the legal regime and S, N and P respectively denote SPR, NSPR and PPR. I will use subgame perfect Nash Equilibrium (SPNE) as my solution concept, and focus on symmetric sub-game equilibria of the second stage game (when multiple firms enter). As explained the objective is to show that weaker patents can lead to more innovation. To see under what conditions this may happen, it is useful to begin by making a few intuitive observations.

First, as demonstrated in the previous section when $E(W) = E(S)$ (where $W \in \{N, P\}$, and W stands for *weak*), it follows that strong patents cause more innovation. Hence, if weak patents are to result in more innovation, it must be the case that the number of entrants under weak patent regimes and the strong patent regime are different (i.e. $E(W) \neq E(S)$). Next it should be intuitively clear that under a pure strategy equilibrium, a weak patent regime cannot attract more firms than a strong patent regime (i.e. $E(W) \leq E(S)$). This is because a strong patent regime rewards successful firms with greater expected payoffs by providing a single inventor with monopoly rents. Therefore, it must be true that $E(W) < E(S)$ in any equilibrium where weak patents lead to more innovation.

To make the next observation let $c^*(L)$ denote the symmetric equilibrium investment by each entrant under regime L. If there are necessarily fewer entrants under a weak patent regime (i.e. $E(W) < E(S)$), the only way that weak patents can generate a higher aggregate likelihood of invention is if $c^*(W) > c^*(S)$. In particular, strong patents retard technological progress iff:

$$\iota(W) = 1 - (1 - p(c^*(W))^{E(W)} > 1 - (1 - p(c^*(S))^{E(S)} = \iota(S) \tag{6}$$

where $\iota(L)$ denotes the aggregate innovation probability under regime L, $1-p(c^*(L))$ denotes the probability that an entrant fails in inventing the product, and similarly $(1 - p(c^*(L))^{E(L)}$ denotes the probability that all firms are unsuccessful.

This condition can only hold, if in equilibrium the elimination of a rival leads an entrant to significantly increase its level of investment. Such an increase will be observed if the marginal expected benefits from increasing investment is high. These marginal benefits will be high, if $p'(c)$ is large for $c > c^*(S)$. The next proposition exploits this final observation to demonstrate that there exist economies in which strong patents lead to less innovation.

Proposition 2: *Weaker patent protections can lead to more innovation under pure strategy subgame perfect Nash Equilibria.*

Proof: *See Appendix.*

Note that this result is driven by the fact that firms reduce their investments when they are competing against more rivals. This happens in a pure strategy SPNE, because firms expect to share the prize with others more often. As such, the expected size of the prize is smaller when there are more firms engaging in R&D, making the marginal benefit from investment smaller. This leads firms to make smaller investments under a strong patent regime.

One may, however, reasonably criticize the emphasis on pure strategy SPNE. Under such equilibria, firms are constrained to enter and incur fixed costs of F in the first period with a probability of 1 or 0. By focusing on this type of equilibria, one immediately eliminates potential coordination problems. One particular and important coordination problem, for instance, occurs when all firms choose to enter with probability $r < 1$, and therefore ex-post there are no entrants with a probability of $(1 - r)^{\overline{E}}$. This problem is eliminated under a pure strategy SPNE, because by assumption, monopoly rents are high enough to attract investment by a single firm, when that firm knows that there will be no other entrants. One may claim that the existence of such coordination problems may reduce aggregate invention probabilities under weak patent regimes more than they reduce them under strong patent regimes. The next proposition establishes the fact that results summarized earlier are not affected if one focuses on mixed strategies instead of pure strategies.

Proposition 3: *Weaker patent protections can lead to more innovation under mixed strategy subgame perfect Nash Equilibria.*

Proof: *See Appendix.*

Propositions 2 and 3 demonstrate that when the number of R&D firms are endogenously determined, the conventional view that strong patents lead to more innovation than weak patents need not be true. This result is driven by the fact that R&D firms may decrease their investments when they suspect that they will be confronting more rivals. Since strong patent regimes provide higher expected profits to entrants compared to weak patent regimes they may attract more R&D firms who spend less on research. As such it is not necessarily true that stronger patents result in more innovation. Furthermore, these results are robust to the choice of equilibria, and are obtained under pure as well as mixed strategy equilibria.

IV. Endogenous Number of Firms with Incomplete Information

As discussed in the previous section, strong patent regimes may attract a high number of R&D firms that invest little in research, whereas weak patent regimes may attract few firms who invest heavily in R&D. However, in the full information framework it is impossible for rational firms to abandon a research project for which they have already purchased the necessary facilities to conduct R&D (i.e. incurred fixed costs of F in the first stage). This follows, because abandoning a project in the second period would result in negative payoffs (i.e. $-F$). A firm receiving a negative pay-off has a profitable deviation from its current strategy, namely not entering in the first period. As such, abandoning a research project can never be part of a SPNE strategy.[24]

To incorporate the realistic possibility of firms abandoning research projects for which they have already incurred some costs, it is sufficient to introduce heterogeneity across firms. If firms have heterogenous invention technologies that they realize only after making initial investments, abandoning projects may become a rational strategy for technologically inferior R&D firms. This possibility, and its effects on the impact of patent strength on innovation, is best studied by analyzing an incomplete information game where firms lack knowledge about each other's innovation technologies.

Let λ_i be firm i's technology parameter reflecting its productivity, so that p_i, the probability of invention, is not only a function of investment (c_i) but also λ_i. For simplicity let $p_i(c_i, \lambda_i) = \lambda_i g(c_i)$ where g_i is a function reflecting the impact of investment on p_i. Furthermore, assume that $\lambda_i \in \{\lambda^l, \lambda^h\}$, with $\lambda^h > \lambda^l$, so that λ^h reflects technological superiority. As in the previous section, in the first period $E(L)$ firms make small investments of F to purchase the necessary facilities to conduct R&D. After such purchases are made, they realize their technology parameter λ_i, where each firm draws λ^h $[\lambda^l]$ with probability q $[1-q]$. Before paying fixed costs of F, however, firms only have knowledge of q, and know that q is common for all firms. At no stage of the game do firms realize their rivals' technology parameter. In the second period, firms choose their investments (c_i), where firm i is said to abandon its project if $c_i = 0$.

I will focus on symmetric sub-game perfect Bayesian Nash Equilibria (SPBNE) to analyze this game. In such equilibria, a firm's investment decision depends only on the legal regime and its

[24]This reasoning fully explains why abandoning R&D efforts cannot be part of a pure strategy SPNE. Demonstrating the same for mixed strategy symmetric SPNE is slightly more complicated. In a mixed strategy SPNE, due to coordination problems, there can be instances in which multiple firms end up non-profitably entering the second period, and still have positive expected payoffs ex-ante. A symmetric equilibrium where all such firms abandon efforts, however, cannot be an equilibrium, because all firms would have profitable deviations, namely slightly increasing their investments. As such, in equilibrium firms must be making positive investments in all such sub-games.

technology parameter (λ). A few intuitive observations can be made regarding pure strategy SPBNE to show that firms may abandon efforts more often under strong patent regimes. First, intuitively, firms are more likely to abandon projects when they are technologically inferior, and they suspect that there are firms that are technologically superior. Furthermore, the greater the number of firms, the more likely it is that there are superior firms, and the more likely it is that there are many of them. Second, as demonstrated in the previous section, strong patent regimes attract more firms to the second stage than weak patent regimes. As such, a firm with a bad technology draw is more likely to abandon efforts under a strong patent regime. In other words, more firms are likely to drop out of the race early under strong patent regimes. The next proposition demonstrates that there are economies where strong patent regimes lead firms to abandon research more often, and that this contributes to weaker patents resulting in more innovation.

Proposition 4: *There are pure strategy subgame perfect Bayesian Nash Equilibria where (i) Strong Patent Regimes lead firms to abandon R&D more often, and (ii) Weaker patent protections can lead to more innovation.*

Proof: *See Appendix.*

The emphasis on pure strategy equilibria is prone to the same type of criticism summarized in the previous section. As such, it is useful to note that results do not depend on equilibria being pure strategy equilibria. This is demonstrated by the following proposition:

Proposition 5: *There are mixed strategy subgame perfect Bayesian Nash Equilibria under weak patent regimes where (i) Strong Patent Regimes lead firms to abandon R&D more often, and (ii) weaker patent protections lead to more innovation.*

Proof: *See Appendix.*

Due to incomplete information firms may abandon R&D projects when they believe they are technologically inferior to their rivals, and strong patent protections may lead more firms to abandon R&D efforts. This observation, together with those demonstrated in the previous section, implies that strong patent regimes may retard technological progress in two ways. First, they may incentivize technologically superior firms to make small investments. Second, they may lead technologically inferior firms to abandon research. These two effects, when combined, may overcome the positive effect of strong patent regimes, namely increasing the number of initial entrants. As such, as demonstrated in propositions 4 and 5, strong patent regimes may actually retard technological progress. As in the previous section, these results are robust to the choice of equilibria and are obtained under pure as well as mixed strategy equilibria.

V. Conclusion

According to reward theory, the main function of patents is to give potential inventors heightened incentives to engage in R&D. Under this theory, the optimal strength of patents depends on a use-creation tradeoff; the inevitable production of dead-weight losses in the ex-post market for the invention for the purpose of fostering technological progress. This follows from the conventional view that strong patents increase the rate of innovation. In this paper, by making use of game theory, I show that there is a caveat in the conventional view that has not yet been formalized in the literature, and demonstrate that strong patents may actually retard technological progress.

The main intuition driving results demonstrated in this paper can be summarized as follows. Strong patents increase the value of becoming an inventor. As such more firms are attracted to R&D. Confronted with more rivals, firms rationally discount the probability that they will be the first to obtain a patent, and may therefore reduce their R&D investments. Furthermore, under strong patent regimes more firms estimate that they have 'fallen behind' in their research, simply because they estimate that other firms may have superior R&D technologies. These firms find it in their best interest to abandon R&D projects. These two effects lead to a lower invention probability per R&D firm, which in turn may lead to a lower aggregate invention probability.

Accordingly, this paper demonstrates that technological progress is not globally and monotonically increasing in patent strength as is conventionally claimed. This paper does not, however, identify specific conditions under which such non-monotonicity is likely to be observed. The fact that there is some empirical evidence suggesting that such non-monotonicity exists leads one to believe that upon more careful examination a testable hypothesis can be formed as to when adverse effects of strong patents are likely to be significant and observable. A good direction for future research is the identification of specific conditions under which reduction in effort and abandoning of projects dominate the positive effects of strong patents. Once identified, these conditions can be stylized in the context of patentability conditions to discuss policy implications and potential patent reforms.

Appendix

Note: In the proofs that follow, when the symbol '$\approx$' is used to denote approximate equality, numbers are rounded up to the 5^{th} decimal.

Proof of Proposition 2: The economy, and rents under SPR, PPR and NSPR summarized by Table 1, constitute an example where weak patents (i.e. PPR and NSPR) lead to more innovation than strong patents.

Table 1: Parameters constituting a counter-example.

$\overline{E} = 2$

$F = 7/8$

$c_i \geq 0$

$$p(c) = \begin{array}{l} 1 - \frac{1}{c+1} \text{ if } c \leq 1 \\ \frac{1}{4} + \frac{1}{4}c \text{ if } 3 \geq c \geq 1 \\ 1 \text{ if } c > 3 \end{array}$$ [25]

$\pi_m = 5$

$\pi_d = 1$

$\delta = 0.9$

To describe the symmetric SPNE in this economy proceed by backward induction and consider subgames that could be played in the second period. In subgames where $E = 1$, it follows that the single firm's pay-off is $p(c)\beta(L)\pi_m - c$ and is maximized at $c^{1,*} = 3$, where $c^{1,*}$ denotes the equilibrium investment of the single firm. The single entrant's second-period pay-off of from investing $c^{1,*}$ is:

$$U(S) = U(P) = 2, \text{ and } U(N) = 1.5 \quad \text{(A.1.)}$$

When two firms enter the second stage, as shown in eqn. (5), a symmetric sub-game equilibrium is achieved when:

$$p'(c^{2,*}) = \frac{1}{\beta(L)\pi_m - p(c^{2,*})(\beta(L)\pi_m - \gamma(L))} \tag{A.2.}$$

where c_2^* denotes the equilibrium investment of both firms in the sub-game with two entrants, and $\gamma(L)$ is defined in (3). Using the values in Table 1, one can easily verify that $c^{2,*} < 1$ must hold under every regime, since otherwise the right hand side of (A.2.) is always greater than its left hand side. Accordingly, by plugging in the expression for $p(c)$ from Table 1 into (A.1.), re-arranging, and manipulating we get:

$$\beta(L)\pi_m - \gamma(L) + (c^{2,*}+1)\gamma(L) - \left(c^{2,*}+1\right)^3 = 0 \tag{A.3.}$$

Solving this cubic expression for $c^{2,*}+1$, reveals that

$$c^{2,*} = \sqrt[3]{\frac{1}{2}(\beta(L)\pi_m - \gamma(L)) + \sqrt{\frac{1}{4}(\beta(L)\pi_m - \gamma(L))^2 - \frac{1}{27}\gamma(L)^3}} + \frac{1}{3}\frac{\gamma(L)}{\sqrt[3]{\frac{1}{2}(\beta(L)\pi_m - \gamma(L)) + \sqrt{\frac{1}{4}(\beta(L)\pi_m - \gamma(L))^2 - \frac{1}{27}\gamma(L)^3}}} - 1 \tag{A.4.}$$

Plugging in the relevant values from Table 1, we have that:

$$c^{2,*}(S) \approx 0.945\,51,\ c^{2,*}(P) \approx 0.796\,32,\ \text{and}\ c^{2,*}(N) \approx 0.860\,02 \tag{A.5.}$$

where S, N and P respectively denote SPR, NSPR and PPR. These investments yield both firms second-stage expected pay-offs of:

$$V(S) \approx 0.893\,99,\ V(P) \approx 0.634\,13,\ \text{and}\ V(N) \approx 0.739\,63 \tag{A.6.}$$

Having determined the equilibria of all possible sub-games, we can determine pure strategy symmetric SPNE by constructing the following normal form game which incorporates firms' pay-offs under each possible subgame's equilibrium:

Table 2 Game Matrix

	Enter	Don't
Enter	$V(L) - 7/8$; $V(L) - 7/8$	$U(L) - 7/8$; 0
Don't	0 ; $U(L) - 7/8$	0 ; 0

where the subtraction of 7/8 reflects fixed costs of entry. Plugging in $V(L)$ and $U(L)$ as expressed in (A.6.) and (A.1.) reveals that in a symmetric pure strategy SPNE both firms enter under SPR, and only a single firm enters under weak patent regimes (i.e. PPR and NSPR). As such, the pure strategy equilibrium probability of invention under SPR is given by:

$$\iota(S) = 1 - (1 - p(c^{2,*}(S)))^2 \approx 0.735\,80 \tag{A.7.}$$

And the equilibrium probability of invention under weak patents are given by

$$\iota(P) = \iota(N) = p(c^{1,*}(P)) = p(c^{1,*}(N)) = 1 \tag{A.8.}$$

This proves proposition 2, since $\iota(S) < \iota(P) = \iota(N)$. Q.E.D.

Proof of Proposition 3: To calculate invention probabilities under weak patent regimes under mixed strategy SPNE, let $r^*(L)$ denote each firm's equilibrium probability of entering in the first period. Table 2 implies that this probability is given by:

$$\frac{r^*(L)}{1-r^*(L)} = \frac{U(L)-7/8}{7/8-V(L)} \tag{A.9.}$$

Plugging in the expressions for $V(P), V(N), U(P)$, and $U(N)$ reveals that

$$r^*(P) \approx 0.823\,65, \text{ and } r^*(N) \approx 0.821\,97 \tag{A.10.}$$

Invention probabilities under these regimes are given by:

$$\iota^M(L) = (r^*(L))^2(1-(1-p(c^{2,*}(L)))^2) + 2(1-r^*(L))r^*(L) \tag{A.11.}$$

Plugging in the values for $r^*(P)$ and $r^*(N)$ from eqn. (A.10.) and the values for $c^{2,*}(P)$ and $c^{2,*}(N)$ from (A.5.) we have that:

$$\iota^M(P) \approx 0.758\,66, \text{ and } \iota^M(N) \approx 0.773\,02 \tag{A.12.}$$

Note that there are no mixed strategy equilibria under SPR, and that $\iota^M(P), \iota^M(N) > \iota(S) \approx 0.735\,80$. This proves the claim in proposition 3. Q.E.D.

Proof of Proposition 4:

The economy, and rents under SPR, PPR and NSPR summarized by Table 3, constitute an example where weak patents (i.e. PPR and NSPR) lead to more innovation than strong patents.

Table 3: Parameters constituting a counter-example.

$\overline{E} = 2$

$F = 0.8$

$c_i \geq 0$

$\lambda_i \in \{1/4, 1\}$

$p(c, \lambda) = \lambda(g(c))$.

$$g(c) = \begin{array}{ll} 1-\frac{1}{1+c} & \text{if} \quad c \leq 1 \\ \frac{1}{4}+\frac{c}{4} & \text{if} \quad 3 \geq c > 1 \\ 1 & \text{if} \quad c > 3 \end{array}$$ [26]

$q = 0.9$

$1-q = 0.1$

$\pi_m = 5$

$\pi_d = 2$

$\delta = 0.9$

To describe the symmetric SPBNE in this economy proceed by backward induction and consider subgames that could be played in the second period. In sub-games where $E = 1$, it follows that the single firm's pay-off is $p(c,\lambda)\beta(L)\pi_m - c$ and is maximized at

$$c^{1,*} = \begin{array}{ll} 3 & \text{if} \quad \lambda = 1 \\ \frac{\sqrt{5}}{2} - 1 \approx 0.118\,03 & \text{if} \quad \lambda = 1/4 \text{ and } L \in \{S, P\} \\ \frac{3}{4}\sqrt{2} - 1 \approx 0.060\,66 & \text{if} \quad \lambda = 1/4 \text{ and } L = N \end{array} \tag{A.13.}$$

which can be verified by plugging in the functional forms and values in Table 3. It should also be noted that these investments result in 2nd period expected pay-off's of:

$$\begin{aligned} U(P) &= U(S) \\ &= qg(3)(\pi_m - 3) + (1-q)\frac{1}{4}g(\frac{\sqrt{5}}{2} - 1)(\pi_m - (\frac{\sqrt{5}}{2} - 1)) \\ &\approx 1.812\,9 \end{aligned} \tag{A.14.}$$

and that

$$\begin{aligned} &U(N) \\ &= qg(3)(\delta\pi_m - 3) + (1-q)\frac{1}{4}g(\frac{3\sqrt{2}}{4} - 1)(\delta\pi_m - (\frac{3\sqrt{2}}{4} - 1)) \\ &\approx 1.375\,4 \end{aligned} \tag{A.15.}$$

When $E = 2$ a firm's strategy is a mapping from its technology draw to its investment. Formally, $s_i : \{1/4, 1\} \to C = R_+ \cup \{0\}$, denotes player i's strategy. The pay-off firm i gets as a function of its type ($\lambda_i \in \{1/4, 1\}$), action (c_i) and its rival's type (λ_j) and action (c_j) is given by:

$$u_i(c_i, c_j, \lambda_j; \lambda_i) = p(c_i, \lambda_i)(\beta(L)\pi_m(L) - p(c_j, \lambda_j)(\beta(L)\pi_m(L) - \gamma(L))) \tag{A.16.}$$

where $\gamma(L)$ is defined in (3).

A subgame's Bayesian Nash Equilibrium (BNE) $S^* = (s_1^*, s_2^*)$ must satisfy the following condition:

s_i^* solves

$$\max_{c_i \in C} qu(c_i, s_j^*(1), 1; \lambda_i) + (1-q)u(c_i, s_j^*(1/4), 1/4; \lambda_i) \tag{A.17.}$$

for all $\lambda_i \in \{1/4, 1\}$, and all players $i \in \{1, 2\}$. The following Lemma is useful in determining symmetric BNE of sub-games.

Lemma 1: *In an economy summarized by Table 3 low types do not make positive investments in a symmetric BNE of a subgame with two entrants in any patent regime.*

Proof: To ease notation let $Z(L) = q(\beta(L)\pi_m(L) - p(c_j^l, 1)(\beta(L)\pi_m(L) - \gamma(L))) + (1-q)(\beta(L)\pi_m(L) - p(c_j^h, 1/4)(\beta(L)\pi_m(L) - \gamma(L)))$, where c_j^l and c_j^h denote firm j's investments when it is a low or high type respectively. Next, suppose low types were making positive investments in symmetric equilibrium, this would imply:

$$\frac{1}{4}g'(0) = \frac{1}{4} > \frac{1}{Z(L)}, \text{ or } Z(L) > 4 \tag{A.18.}$$

In this case, a high type's expected pay-off from investing c would be given by $Z(L)g(c) - c$, implying that he would choose $c = 3$, since $Z(L) > 4$. But if this were true, $Z(L) = q\gamma(L) + (1 -$

$q)(\beta(L)\pi_m(L) - p(c_j, 0.25)(\beta(L)\pi_m(L) - \gamma(L))) < q\frac{\pi_m}{2} + (1-q)\pi_m = 2.25 + 0.5 = 2.75$, which contradicts the initial supposition. Q.E.D.

Given Lemma 1, firm i's expected second stage pay-off when he has a high technology draw, is expressed by:

$$g(c_i)(\beta(L)\pi_m(L) - qg(c_j)(\beta(L)\pi_m(L) - \gamma(L)) - c_i \tag{A.19.}$$

As such, in a symmetric equilibrium, $s_i^*(1) = s_j^*(1) \equiv c^{2,*}$, must satisfy:

$$g'(c^*) = \frac{1}{(\beta(L)\pi_m(L) - qg(c^*)(\beta(L)\pi_m(L) - \gamma(L))} = \frac{1}{Z(c^*)} \tag{A.20.}$$

By plugging in the appropriate $\beta(L)\pi_m(L)$ and $\gamma(L)$'s in each regime, we can obtain the equilibrium investments under each regime. Using values in Table 3, one can easily verify that $c^{2,*} < 1$ must hold under every regime, since otherwise the right hand side of (A.2.) is always greater than its left hand side. Accordingly, by plugging in the expression for $p(c)$ from Table 3 into (A.20.), re-arranging, and manipulating we get:

$$q(\beta(L)\pi_m - \gamma(L)) + ((1-q)\beta(L)\pi_m + q\gamma(L))(c^{2,*}+1) - \left(c^{2,*}+1\right)^3 = 0 \tag{A.21.}$$

Solving this cubic expression for $c^{2,*}+1$, reveals that

$$c^{2,*} = \sqrt[3]{\frac{1}{2}(q(\beta(L)\pi_m - \gamma(L))) + \sqrt{\frac{1}{4}(q(\beta(L)\pi_m - \gamma(L)))^2 - \frac{1}{27}((1-q)\beta(L)\pi_m + q\gamma(L))^3}} + \frac{1}{3}\frac{((1-q)\beta(L)\pi_m + q\gamma(L))}{\sqrt[3]{\frac{1}{2}(q(\beta(L)\pi_m - \gamma(L))) + \sqrt{\frac{1}{4}(q(\beta(L)\pi_m - \gamma(L)))^2 - \frac{1}{27}((1-q)\beta(L)\pi_m + q\gamma(L))^3}}} - 1 \tag{A.22.}$$

Plugging in the relevant values from Table 3, we have that:

$$c^{2,*}(S) \approx 0.972\,48,\ c^{2,*}(P) \approx 0.924\,34, \text{ and } c^{2,*}(N) \approx 0.884\,09 \tag{A.23.}$$

where S, N and P respectively denote SPR, NSPR and PPR. These investments yield both firms second-stage expected payoffs of:

$$V(S) \approx 0.851\,15,\ V(P) \approx 0.768\,96, \text{ and } V(N) \approx 0.703\,45 \tag{A.24.}$$

Having determined the equilibria of all possible sub-games, we can determine pure strategy symmetric SPBNE by constructing the following normal form game which incorporates firms' payoffs under each possible subgame's equilibrium:

Table 4 Game Matrix

	Enter	Don't
Enter	$V(L) - 4/5$;$V(L) - 4/5$	$U(L) - 4/5$; 0
Don't	0 ; $U(L) - 4/5$	0 ; 0

where 4/5 reflects fixed costs of entry. Plugging in $V(L)$ and $U(L)$ as expressed in (A.24.) and (A.14.) reveals that in a symmetric pure strategy SPBNE both firms enter under SPR, and only a single firm enters under weak patent regimes (i.e. PPR and NSPR). This implies that, under SPR, per Lemma 1, entrants with a low λ abandon R&D, but as demonstrated in (A.13.) abandonment does not occur when there is a single entrant, and therefore under weak patents. This demonstrates part (i) of the proposition.

The aggregate invention probability under SPR is given by:

$$\iota(S) = 1 - (1 - qg(c^{2,*}(S)))^2 \approx 0.677\,72 \quad \text{(A.25.)}$$

The same, under weak patents is given by:

$$\iota(P) = q(g(c^{2,*}(P)) + (1-q)\frac{1}{4}g(c^{1,*}(P)) \approx 0.902\,64 \quad \text{(A.26.)}$$

and,

$$\iota(N) = q(g(c^{2,*}(P)) + (1-q)\frac{1}{4}g(c^{1,*}(N)) \approx 0.901\,43$$

This proves part (ii) of proposition 4 since $\iota(S) < \iota(N) < \iota(P)$. Q.E.D.

Proof of Proposition 5: To calculate invention probabilities under weak patent regimes under mixed strategy SPBNE, let $r^*(L)$ denote each firm's equilibrium probability of entering in the first period. Table 4 implies that this probability is given by:

$$\frac{r^*(L)}{1 - r^*(L)} = \frac{U(L) - 4/5}{4/5 - V(L)} \quad \text{(A.27.)}$$

Plugging in the expressions for $V(P), V(N), U(P)$, and $U(N)$ reveals that

$$r^*(P) \approx 0.970\,27, \text{ and } r^*(N) \approx 0.856\,31 \quad \text{(A.28.)}$$

Invention probabilities under these regimes are given by:

$$\iota^M(L) = (r^*(L))^2(1 - (1 - qp(c^{2,*}(L)))^2) + 2(1 - r^*(L))r^*(L) \quad \text{(A.29.)}$$

Plugging in the values for $r^*(P)$ and $r^*(N)$ from eqn. (A.10.) and the values for $c^{2,*}(P)$ and $c^{2,*}(N)$ from (A.5.) we have that:

$$\iota^M(P) \approx 0.695\,72, \text{ and } \iota^M(N) \approx 0.734\,65 \quad \text{(A.30.)}$$

Note that there are no mixed strategy equilibria under SPR, and that $\iota^M(N) > \iota^M(P) > \iota(S) \approx 0.677\,72$. This proves part (ii) of proposition 5.

The expected number of firms abandoning projects under weak patent regimes under mixed strategy symmetric SPBNE is given by $A(L) = (r^*(L))^2(2(1-q)^2 + 2(1-q)q) = 2(1-q)(r^*(L))^2$, since (i) abandonment occurs only when $E = 2$ (which occurs with a probability of $(r^*(L))^2$), (ii) and given $E = 2$ two firms abandon R&D when they both have a low λ (which happens with a probability of $(1-q)^2$ given $E = 2$), and (iii) given $E = 2$ a single firm abandons R&D when only that firm has a low λ (which happens with a probability of $2(1-q)q$ given $E = 2$). The same is true under SPR, but the probability that $E = 2$ is unity. Hence, the expected number of firms abandoning R&D under SPR is given by $A(S) = 2(1-q) > A(W) = 2(1-q)(r^*(W))^2$ for all $W \in \{P, N\}$. This demonstrates part (i) of proposition 5. Q.E.D.

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