(When) Do Stronger Patents Increase Continual Innovation?

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Abstract: Under continual innovation, greater patent strength expands innovating firms' profit against imitation, but also shifts profit from current to past innovators. We show how the impact of patents on innovation, as determined by these two opposing effects, varies with industry characteristics. When the discount factor is sufficiently high, the negative profit division effect is negligible, and innovation monotonically increases in patent strength; otherwise, innovation has an inverted-U relationship with patent strength, and stronger patents are more likely to increase innovation when the discount factor or the fixed innovation cost is higher. We also show how the impact of patents on innovation may change with firms' innovation capability and with the intensity of competition from imitators.

Keywords: Continual innovation, patents, patent strength, profit expansion, profit division

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1. INTRODUCTION

A central issue in the economics of innovation is how patents affect innovation incentives. In the standard static framework for a single innovation (e.g., Gilbert and Shapiro, 1990; Klemperer, 1990; Gallini, 1992), stronger patent protection encourages innovation by protecting the innovator's profits against potential imitation, albeit it may cause static monopoly distortion. A key feature of innovation, however, is that it is cumulative. For example, current innovation in the biotechnology and software industries can be used as a base of future improvement (Scotchmer, 2004). This consideration has led to the examination of patent policy in a two-stage innovation framework where a second innovation builds upon the first (e.g., Green and Scotchmer, 1995; and Scotchmer, 1996).[1] This approach emphasizes the division of profit between innovators, and argues that it is necessary to transfer profit from follow-on to initial innovators in order to provide sufficient incentives for the fundamental initial innovation. More recent advances in the literature have addressed the issue of patent strength under continual innovation, recognizing that firms may rotate their roles as past and current innovators over time. While several studies have found that stronger patents further innovation by delaying the next patentable discovery (e.g., O'Donoghue 1998; O'Donoghue et al, 1998; and Hunt, 2004),[2] Segal and Whinston (2007), focusing on profit division, demonstrates that increasing patent strength actually reduces continual innovation due to a "front-loading" effect.[3] Thus, the important question of how patents will impact continual innovation remains unsettled. In this paper, we reconsider this issue more generally in a framework where the profit expansion and division

[1] See also Chang, 1995; Matutes, et al, 1996; Van Dijk, 1996; Denicolò, 2000; and Denicolò and Zanchettin, 2002.

[2] In particular, O'Donoghue et al (1998) suggests granting leading breadth while O'Donoghue (1998) proposes using a patentability requirement to stimulate R&D investment. Hunt (2004) shows the existence of a unique patentability standard that maximizes the rate of innovation.

[3] An innovator benefits from the innovation immediately as an entrant but with a discount as the future incumbent. Thus, stronger patent protection, which shifts innovation profit from the entrant to the incumbent, reduces innovation incentive. Segal and Winston (2007) obtained this insight in the context of antitrust policy, but it equally applies to patent protection, as discussed in Vickers (2010).

effects are both present, and investigate whether (when) stronger patents will lead to higher or lower industry innovation.

We study a dynamic model of continual innovation that considers explicitly the interactions between the two distinctive roles of patents: dividing profits between sequential innovators and expanding profits from innovation by deterring imitation. Our stylized economy consists of two potential innovating firms and a competitive fringe of imitators. In each period, one of the innovating firms is the incumbent, who, through innovation at an earlier period, can produce a product of a certain quality; whereas the other is the potential entrant who, if successful in discovering a higher-quality product through R&D, will enter the industry, replace the current incumbent, and becomes the new incumbent next period. Stronger patent protection expands the profits of the innovators against imitators, but also shifts profits from current to past innovators. The net impact of these two effects on continual innovation, as we shall demonstrate, varies with industry fundamentals.

To allow for more general analysis, we first consider a model with reduced-form payoffs for various players, without specifying the functional forms of payoffs. In this general model, we find that maximum patent protection is most conducive to innovation when the discount factor is above a critical value; otherwise, the industry innovation rate is an inverted-U function of patent strength. The intuition for this finding is the following: In industries where discovery potentially occurs highly frequently (or the discount factor is sufficiently large), the frequent rotation of a firm's role as an incumbent or an entrant under continual innovation means that the profit division effect is negligible, and it is the joint profit of the innovators—past and present—that determines R&D incentives. Stronger patent protection expands this joint profit at the expense of the imitators, thereby increasing innovation. When the discount factor is not too high, however, the profit expansion effect initially dominates and is then dominated by the profit division effect, so that some intermediate level of patent protection, which increases in the discount factor, can properly balance the two opposing effects to provide the highest innovation incentive. Notice that our finding is in contrast to the result suggested by Segal and Whinston (2007) that stronger patents would reduce innovation in innovative industries. This is due to their focus on the profit division effect whereas our analysis also incorporates the role of patents in expanding innovators' profits against imitation.

We also show that when firms' innovation capability is higher, stronger patent increases innovation if it enlarges innovating firms' net profit gain from a new discovery (in periods with or without entry), but it decreases innovation otherwise. Intuitively, when the innovation capability is higher, new discovery (or success of the potential entrant) is more likely, and hence to increase innovation incentive it is more desirable to have stronger patent protection that would increase the joint profits of the innovating firms in the entry period. However, a higher innovation capability also raises the probability that the incumbent (the past innovator) will be replaced, and hence enhanced protection, which increases the profit of the incumbent (in the period of no entry), is also less useful in encouraging innovation. Thus, whether stronger patents will encourage innovation under higher innovation capability depends on how the net profit of the innovating firms from a new discovery varies with patent protection. An immediate implication of this result is that patent protection need not be higher in a country or an industry in which firms have higher innovation capabilities. While previous studies have also suggested this possibility[4], our analysis points to a new mechanism for this possible outcome.

With additional assumptions that parameterize the model, we further find that increased competition, in the sense of reduced horizontal product differentiation between the innovating and imitating firms, partially substitutes for patent protection in promoting innovation when the discount factor is relatively small. When the discount factor is relatively large, however, starting from relatively low intensity of competition, increasing competition intensity is initially complementary to but eventually becomes partially substituting for patent

[4] For instance, Chen and Puttitanun (2005) find empirical evidence for a U-shaped relationship between the strength of intellectual property rights (IPRs) and a country's innovation capability (measured by its leve of development).

protection in stimulating innovation. We also derive new results on how innovation costs may affect patent protection: high marginal innovation cost tends to reduce the need for strong patent strength, whereas high fixed innovation cost tends to require greater patent protection. As we shall explain in detail, the intuition for these results can also be found from considering the interactions between the profit expansion and division effects.

In their recent book, Burk and Lemley (2009) commented that "...innovation works differently in different industries, and (that) the way patents affect that innovation also differs enormously by industry. The question for patent policy is how to respond to these differences." (page 5). Our findings are in broad support of their views on the different roles patents may play in different industries. We contribute to the debate on patent policy by demonstrating in a formal model *how* the impacts of patents on innovation incentives may vary systematically with industry characteristics, and by clarifying the underlying economic forces that result in these variations.

The rest of the paper proceeds as follows. Section 2 formulates a general model with reduced-form payoffs. Section 3 analyzes this model and establishes analytical results on how innovation depends on patent strength and how their relationship varies with the discount factor and firms' innovation capability. Section 4 parametrizes the general model with additional assumptions to investigate how competition from imitators and innovation costs may interact with patent protection to affect innovation. Section 5 concludes.

2. THE MODEL

We consider a stylized model with discrete time and infinite horizon, $t = 0, 1, 2, ...$ The economy consists of two potential innovating firms and a competitive fringe of imitators. In each period, one of the innovating firms is the "incumbent" I and the other is the "potential entrant" E.[5] At period t, the incumbent, through innovation at an earlier period, can

[5] To simplify notations, we use the same I and E to denote the incumbents and potential entrants at different time periods. Also, for variables that are time invariant, we will drop the time variable t.

produce a product that has quality q_t.[6] The competitive fringe of firms, who do not innovate and merely imitate the incumbent$'s$ product, produce a variety that has quality $q_t^c(\alpha)$, with $q_t^{c\prime}(\alpha) < 0$, where $\alpha \in [0,1]$ is the strength of patent protection. (Thus stronger patents will lower the product quality of the imitating firms.) At the beginning of each period, the potential entrant chooses its R&D rate, or the probability of success, $\lambda\phi \in [0,1]$, where λ can be considered as an industry- or country- specific parameter that measures innovation capability. Thus, λ might be small in a mature industry or in a less developed country, but large in a new industry or in a developed country. The R&D cost $c(\phi)$ is twice differentiable with $c'(\cdot) \geq 0$ and $c''(\cdot) \geq 0$. Without $E's$ entry, I will remain as the incumbent next period. If E is successful, its new product, whose quality is Δ above $I's$ product quality, immediately replaces $I's$ product and will become the incumbent next period, whereas the current incumbent will become the potential entrant next period.

For our main model, to allow for more general analysis, we make reduced-form assumptions about equilibrium profits in each period. Specifically, we assume that in a period without entry, the incumbent's profit is $\pi_m \equiv \pi_m(\alpha)$; and in a period with the entry of E, the joint profit of I and E is $\pi_\Sigma \equiv \pi_\Sigma(\alpha)$, of which I receives $\pi_I = \alpha\pi_\Sigma$ and E receives $\pi_E = (1-\alpha)\pi_\Sigma$. Thus stronger patent protection, in the sense of a higher α, increases the profit share of the current patent holder relative to the entrant (the new innovator). The competitive fringe will always price at their marginal cost, which is normalized to zero. We further assume that $\pi_m'(\alpha) > 0$, $\pi_m''(\alpha) \leq 0$; and $\pi_\Sigma'(\alpha) > 0$, $\pi_\Sigma''(\alpha) \leq 0$, with $\pi_\Sigma'(0) \geq \pi_\Sigma(0)$. Thus, the total profits of innovating firms (with or without entry) are increasing and concave functions of patent strength, and the profit expansion effect is not too small when $\alpha = 0$.

After analyzing the main model, we shall parameterize it with additional functional specifications under which the reduced-form assumptions are satisfied and further comparative static results are obtained.

[6] For $t = 0$, we assume I is able to produce a patentable product with value q_0.

3. ANALYSIS

We focus on stationary Markov perfect equilibria of the infinite-horizon game. Define V_I as the expected present discounted profit of an incumbent, and V_E as that of a potential entrant, both of which are evaluated at the beginning of a period. Consequently, we have:

$$V_I = \pi_m + \delta V_I + \lambda\phi\left[\pi_I - \pi_m + \delta\left(V_E - V_I\right)\right], \tag{1}$$

where $\delta \in (0,1)$ is the discount factor. The first two terms in the right-hand side of (1) denote the expected present discounted value if the incumbent is not replaced, while the third term denotes the loss of the value if it is replaced.

Similarly, the expected present discounted profit that an entrant earns is given by:

$$V_E = \delta V_E + \lambda\phi\left[\pi_E + \delta\left(V_I - V_E\right)\right] - c\left(\phi\right), \tag{2}$$

where the first term in the right-hand side of (2) is the expected present discounted value if the entrant does not innovate, while the second term is the gain of the value if it does.

Following Segal and Whinston (2007), we call $w \equiv \pi_E + \delta\left(V_I - V_E\right)$ the innovation prize.[7] Equation (2) implies that, given the innovation prize w, the optimal R&D rate for entrant E is

$$\Phi\left(w\right) = \arg\max_{\phi\in[0,1]}\left\{\lambda\phi w - c\left(\phi\right)\right\}. \tag{3}$$

As in Segal and Whinston (2007), since $c\left(\phi\right)$ is convex, $\Phi\left(w\right)$ is a continuous and increasing function of w for all $\lambda w \geq c'\left(0\right)$, whereas $\Phi\left(w\right) = 0$ for $\lambda w < c'\left(0\right)$.

From (1) and (2), we find

[7] This is also called the expected capital gain that results from making a patentable discovery in Hunt (2004).

$$V_I = \frac{\lambda\phi\left(1-\delta\right)\pi_I + \left(1-\lambda\phi\right)\left(1-\delta+\delta\lambda\phi\right)\pi_m + \delta\left(\lambda\phi\right)^2\pi_\Sigma - \delta\lambda\phi c\left(\phi\right)}{\left(1-\delta\right)\left(1-\delta+2\delta\lambda\phi\right)}, \tag{4}$$

$$V_E = \frac{\lambda\phi\left(1-\delta\right)\pi_E + \delta\lambda\phi\left(1-\lambda\phi\right)\pi_m + \delta\left(\lambda\phi\right)^2\pi_\Sigma - \left(1-\delta+\delta\lambda\phi\right)c\left(\phi\right)}{\left(1-\delta\right)\left(1-\delta+2\delta\lambda\phi\right)}, \tag{5}$$

and

$$V_I - V_E = \frac{\lambda\phi\left(2\alpha-1\right)\pi_\Sigma + \left(1-\lambda\phi\right)\pi_m + c\left(\phi\right)}{1-\delta+2\delta\lambda\phi}. \tag{6}$$

Substituting (6) into $w = \pi_E + \delta\left(V_I - V_E\right)$ and utilizing $\pi_E = \left(1-\alpha\right)\pi_\Sigma$, we obtain

$$W\left(\phi,\alpha,\lambda\right) = w = \frac{\left(1-\delta\right)\pi_E + \delta\left[\lambda\phi\pi_\Sigma + \left(1-\lambda\phi\right)\pi_m + c\left(\phi\right)\right]}{1-\delta+2\delta\lambda\phi}. \tag{7}$$

Then, given parameter values, the equilibrium innovation rate and innovation prize, $\left(\phi^*,\ w^*\right)$, solve (3) and (7), and we assume that such a solution exists.[8] Since $\Phi\left(w\right)$ is increasing and is independent of α, whether strengthening patent protection is conducive or detrimental to innovation depends on how it affects the innovation prize, w. If an increase in α shifts out (or shifts in) w, then stronger patents increase (or decrease) innovation. That is, stronger patent protection stimulates (stifles) innovation if

$$\frac{\partial W}{\partial \alpha} = \underbrace{-\frac{\left(1-\delta\right)\pi_\Sigma}{1-\delta+2\delta\lambda\phi}}_{\text{profit division}} + \underbrace{\frac{\left[\left(1-\delta\right)\left(1-\alpha\right)+\delta\lambda\phi\right]\pi_\Sigma' + \delta\left(1-\lambda\phi\right)\pi_m'}{1-\delta+2\delta\lambda\phi}}_{\text{profit expansion}} \geq (\leq)\ 0. \tag{8}$$

The first term on the right-hand side of (8) is the *profit division* effect of increasing α on innovation (or on the innovation prize): stronger patent protection shifts profits from the entrant (the new innovator) to the incumbent (the existing patent holder); and, since

[8] Following Segal and Whinston (2007), we can call the functions defined by (3) and (7) the *innovation supply* function and the *innovation benefit* function, respectively. For comparative statics analysis, when there are multiple equilibria, or multiple ϕ^*, we assume that the largest ϕ^* prevails.

the innovator benefits from the innovation as the entrant immediately but as the future incumbent only with a discount, the profit division effect negatively impacts innovation incentives. This corresponds to the front-loading effect in Segal and Winston (2007). The second term on the right-hand side of (8) is the *profit expansion* effect of increasing α on innovation: stronger patent protection reduces imitation, increasing the joint profits of the innovating firms both through the higher joint profits of the (past and present) innovating firms in the period of entry and through the higher profit of the incumbent (the past innovator) when there is no entry. Whether stronger patent protection promotes or hinders innovation depends on the balance of these two effects, either of which may dominate, as we show below:

Proposition 1 *There exists some* $\bar{\delta} \in (0,1)$ *such that (i) when* $\delta > \bar{\delta}$, $\frac{\partial W}{\partial \alpha} > 0$; *(ii) when* $\delta \in \left[0,\ \bar{\delta}\right]$*, there is a unique* $\alpha^* (\delta)$ *so that* $\frac{\partial W}{\partial \alpha} \gtreqless 0$ *for* $\alpha \lesseqgtr \alpha^* (\delta)$, *and* $\alpha^* (\delta)$ *increases in* δ*.*

Proof. See the appendix. ■

An innovator is rewarded both immediately as the entrant and with a discount as the future incumbent. The division of profits affects how the innovation benefits are divided between these two distinctive roles of the innovator; and, by shifting profits away from the entrant to the incumbent, the profit division effect of patent protection impacts negatively on innovation incentive. However, as $\delta \to 1$, the profit division effect goes to zero, since the innovator's gain as the future incumbent is little discounted. Consequently, the profit expansion effect of increasing α, which increases the joint profits of the entrant and the incumbent, must dominate. This suggests that in industries where technology replacements occur sufficiently frequently (i.e., δ is sufficiently high), stronger patent protection tends to increase innovation.[9]

[9] The profit expansion effect, which is not present in Segal and Winston (2007), explains why we reverse their finding that a policy shifting profits to the incumbent reduces innovation. Our result also differs from Bessen and Maskin's (2009) finding that imitation promotes innovation in industries where technol-

For δ not too large ($\delta \leq \bar{\delta}$), the profit division effect becomes significant. The assumption that the profits of the innovating firms—$\pi_m(\alpha)$ and $\pi_\Sigma(\alpha)$—are concave, together with the initial condition that $\pi'_\Sigma(0) > \pi_\Sigma(0)$, ensures that the profit expansion effect will dominate when α is small, but the profit division effect will dominates when α is large. Consequently, innovation incentives rise initially but fall eventually with α, or exhibiting an inverted-U relationship with patent strength.

We next investigate how the innovation capability (λ) of an industry or a country impacts patent policies. For this purpose, suppose that the patent protection that maximizes the innovation prize, α^*, is interior, so that $\frac{\partial W}{\partial \alpha}\big|_{\alpha=\alpha^*} = 0$. Then, from (8), we have

$$\left.\frac{\partial^2 W}{\partial \alpha \partial \lambda}\right|_{\alpha=\alpha^*} = \frac{\delta\phi\left(\pi'_\Sigma - \pi'_m\right)}{2\delta\lambda\phi - \delta + 1}, \tag{9}$$

which immediately implies:[10]

Proposition 2 *A marginal increase in λ raises α^* if $\pi'_\Sigma \geq \pi'_m$ but lowers α^* if $\pi'_\Sigma < \pi'_m$.*

A higher innovation capability (λ) makes new discovery (or success of the potential entrant) more likely, and hence to increase innovation incentive it is more desirable to have a higher α that would increase the profits of the innovating firms when there is entry (i.e., $\pi'_\Sigma > 0$). However, a higher λ also raises the probability that the incumbent will be replaced, and hence a higher α, which increases the profit of the incumbent (the past innovator) ($\pi'_m > 0$), also becomes less useful in encouraging innovation. Thus, whether a higher innovation capability raises or lowers α^* depends on the sign of $\pi'_\Sigma - \pi'_m$, or how the net profit of the innovating firms (both E and I) from a new discovery varies with patent protection.

Our results can shed light on policy discussions concerning patents, and more broadly,

ogy replacements occur frequently—they assume that innovation is sequential and complementary, so that imitation provides complementary elements for the subsequent innovation.

[10] Note that a change in λ also shifts $\Phi(w)$ defined in (3), but the α that maximizes innovation prize (w) will still result in the highest equilibrium innovation rate, ϕ^*.

IPRs. It has been argued that only developed countries benefit from strong IPRs protection (e.g., Chin and Grossman, 1990; Helpman, 1993), and evidence from cross-country studies suggests that the positive effect of patents on innovation is stronger in developed than in developing countries (e.g., Park and Ginarte, 1997; Park, 2005; and Qian, 2007). To the extent that developed countries conduct most innovations and hence also have more frequent innovations, our Proposition 1 is consistent with these arguments and evidence. However, our findings in Propositions 1 and 2 also caution that the relations between IPRs and innovation can be more complex across countries. Developing countries may also have innovations in certain industries, as Chen and Puttitanun (2005) argue and find evidence for. Even though their innovation frequencies or innovation capabilities may be relatively low, stronger patent protection can also stimulate innovation in developing countries, as Proposition 1 suggests. Furthermore, a higher innovation capability in a more developed economy does not always mean that it should have stronger patent protection to stimulate innovation; the key consideration, rather, is how the net profit of the innovating firms from a new technology may vary with patent protection.

4. FURTHER ANALYSIS

We next examine additional comparative statics to explore how competition from imitators and innovation costs interact with patent protection to affect innovation incentives. Specifically, we are interested in the following two questions: (1) To stimulate innovation, should patent protection be stronger or weaker when there is more intense competition from the imitators due to reduced product differentiation. In other words, are competition and patent protection complements or substitutes in promoting innovation? (2) How will the nature of innovation cost, the relative importance of fixed and variable costs for innovation, affect the choice of patent protection? To address these questions, we parameterize the main model by assuming the following: Consumers are uniformly distributed on a Hotelling line with $x \in [0,1]$. Each consumer's value for a product is equal to the product's quality, and a consumer's unit transportation cost is τ. Firm I, and firm E when there is entry, are located at $x = 0$, whereas the competitive fringe of (imitating) firms are located at $x = 1$. Following Green and Scotchmer (1995) and O'Donoghue et al (1998), we assume that $E's$ product will infringe $I's$ patent, which results in I immediately licensing its patent to E. The licensing agreement is such that I will receive α portion of the profit from $E's$ new product in the period of entry.[11] The competitive fringe's product quality in period t is $q_t^c(\alpha) \equiv q_t - l(\alpha)$, with $l(0) \geq 0$, $l'(\alpha) > 0$, and $l''(\alpha) \leq 0$. We assume that $q_0 \geq l(1) + \frac{3}{2}\tau$ to ensure consumers will always purchase in equilibrium. For convenience, we also assume $\lambda = 1$ for the rest of the analysis.

In a period without entry, given $I's$ price p, the marginal consumer indifferent between purchasing from I and the competitive fringe is either at $x = 1$ or solves

$$q_t - p - \tau x = q_t - l(\alpha) - 0 - \tau(1-x).$$

$I's$ equilibrium price p_m maximizes $p\left(\frac{-p+l(\alpha)+\tau}{2\tau}\right)$ if $\frac{-p_m+l(\alpha)+\tau}{2\tau} < 1$, and otherwise p_m equals to $l(\alpha) - \tau$. That is, $I's$ equilibrium price and profit are respectively

$$p_m = \begin{cases} \frac{l(\alpha)+\tau}{2} & if \quad l(\alpha) \leq 3\tau \\ l(\alpha) - \tau & if \quad l(\alpha) > 3\tau \end{cases} \quad ; \quad \pi_m = \begin{cases} \frac{[l(\alpha)+\tau]^2}{8\tau} & if \quad l(\alpha) \leq 3\tau \\ l(\alpha) - \tau & if \quad l(\alpha) > 3\tau \end{cases}.$$

Similarly, in a period with entry, the equilibrium price of E and the joint profits of I and E are respectively

$$p_E = \begin{cases} \frac{l(\alpha)+\Delta+\tau}{2} & if \quad l+\Delta \leq 3\tau \\ l(\alpha)+\Delta-\tau & if \quad l+\Delta > 3\tau \end{cases} \quad ; \quad \pi_\Sigma = \begin{cases} \frac{[l(\alpha)+\Delta+\tau]^2}{8\tau} & if \quad l+\Delta \leq 3\tau \\ l(\alpha)+\Delta-\tau & if \quad l+\Delta > 3\tau \end{cases}.$$

[11] Our analysis will be qualitatively the same if the new product infringes the patent rights of the existing product only with some probability.

For convenience, we focus on situations where consumer heterogeneity is not too high, or $3\tau < l(\alpha) + \Delta$. Then, there are two cases: (1) $3\tau < l(\alpha)$, corresponding to situations where product differentiation (or consumer heterogeneity) is relatively small, so that all consumers will purchase from the innovating firms in equilibrium; and (2) $l(\alpha) \leq 3\tau < l(\alpha) + \Delta$, corresponding to situations where the degree of product differentiation (or consumer heterogeneity) is relatively high (but not too high), so that some consumers will also purchase from the competitive fringe in equilibrium during periods without entry.[12] Recall that the patent strength that maximizes the innovation prize (w) is denoted as α^*, which is assumed to be interior for the rest of the analysis.

Proposition 3 *When $3\tau < l(\alpha)$, α^* increases in τ; and when $l(\alpha) < 3\tau < l(\alpha) + \Delta$, α^* increases in τ if $\delta \leq \delta_1 \equiv \frac{4\tau}{4\tau+3(1-\phi)l'(\alpha)}$ but decreases in τ if $\delta \geq \delta_2 \equiv \frac{4\tau^2}{4\tau^2+(1-\phi)(3\tau-\Delta)l'(\alpha)}$.*

Proof. See the appendix. ■

An increase in τ indicates less severe competition from the competitive fringe. Our result suggests that the effects of competition intensity on IPRs and innovation can be rather subtle: they are in general non-monotonic, and may depend on other factors such as the frequency of innovation in an industry. Specifically, if the discount factor is relatively small ($\delta \leq \delta_1$), increasing competition, in the sense of reducing τ, always lowers α^*. In other words, more competition can partially substitute for patent protection in providing innovation incentives. However, if δ is high enough ($\delta \geq \delta_2$), then starting from relatively low intensity of competition ($l(\alpha) < 3\tau$), increasing competition initially raises α^* but eventually lowers α^* (when $l(\alpha) > 3\tau$). That is, more competition is complementary to patent protection at relatively low competition intensity but becomes partially substituting for patent protection at relatively high competition intensity.

Intuitively, under our functional assumptions, the profit-division effect is always decreasing in τ, while the profit expansion effect is decreasing in τ for large τ but independent of

[12] Notice that $\pi_m' > 0$ and $\pi_\Sigma' > 0$ under the assumption $l'(\alpha) > 0$, and, if $l(\alpha) = \tau\sqrt{\alpha}$, we also have $\pi_m'' < 0$ and $\pi_\Sigma'' < 0$ with $\pi_\Sigma'(0) > \pi_\Sigma(0)$.

τ for small τ.[13] When δ is relatively small, the negative profit division effect is relatively large and dominates. Hence a lower τ enlarges the profit division effect and lowers α^*. When δ is large, the negative profit division effect becomes small, so the profit expansion effect dominates when τ is large and a marginal decrease in τ raises α^*; but as τ further decreases, eventually the profit expansion effect becomes independent of τ, in which case the profit division effect dominates (even though it is small), leading to a lower α^* for a marginal reduction in τ.

There has been an extensive economics literature on how product market competition affects innovation.[14] We depart from this literature by considering competition from imitating firms and how it interacts with patent strength to affect innovation. Competition from the imitators affects R&D incentives not only directly, but also indirectly by altering the balance of the profit expansion and division effects of patent strength on innovation.

Next, we consider how innovation cost may affect the patent protection that maximizes innovation incentive. For this purpose, we specify the functional form of innovation cost as $c(\phi) = \frac{c_1}{2}\phi^2 + K$, where K is the fixed cost.[15] Up to this point, we have focused on how changes in α shifts the "innovation benefit" function defined by (7). Now, in order to evaluate the effects of innovation costs, we explicitly combine the innovation benefit function with the "innovation supply" function, defined by (3), to solve the equilibrium innovation rate ϕ^*, which satisfies[16]

$$c_1\phi = \frac{[1-\delta]\,\pi_E + \delta\left[\phi\pi_\Sigma + (1-\phi)\,\pi_m + \frac{c_1}{2}\phi^2 + K\right]}{1-\delta+2\delta\phi}. \tag{10}$$

[13] When τ is small ($3\tau < l(\alpha)$), all consumers will purchase from the innovating firms. Thus, a marginal change in τ has no impact on the profit expansion effect

[14] Aghion et al. (2005), which discusses and builds on this literature, finds that the relationship between product market competition (PMC) and innovation is an inverted U-shape: inceasing competition initially stimulates innovation but hinders innovation at higher levels of competition.

[15] Our qualitative results will hold under the alternative asumption that $c(\phi) = c_1\phi^\beta + K$ for $\beta > 0$.

[16] The second-order condition will be satisfied if either the discounted factor or the fixed cost is large.

Denote the innovation-maximizing α by α^*. The proposition below assumes

$$\frac{l''(\alpha)}{l'(\alpha)} \leq \frac{8(1-\delta)\tau - \delta l'(\alpha)}{4\tau(\alpha\delta + 1 - \alpha)} \tag{11}$$

at $\alpha = \alpha^*$, which holds if $l(\alpha)$ is sufficiently concave.[17]

Proposition 4 *Assume that (11) holds at $\alpha = \alpha^*$. Then, a marginal increase in c_1 weakly lowers α^* while a marginal increase in K weakly raises α^*.*

Proof. See the appendix. ■

Therefore, the innovation-maximizing patent strength tends to be higher in industries with higher fixed and/or lower marginal innovation cost. One way to see the intuition for Proposition 4 is the following. Holding all else constant, as the innovation probability (ϕ) becomes higher, the profit expansion effect becomes more important relative to the profit division effect, as can be seen from (8) where the ratio of the second term to the first term rises with ϕ. On the other hand, the equilibrium innovation rate (ϕ^*) tends to decrease in marginal innovation cost (c_1) but to increase in fixed cost (K), as can be determined from the equilibrium condition for ϕ^*, equation (10). Therefore, an increase in K, or a decrease in c_1, tends to raise ϕ^*, which enhances the relative importance of the profit expansion effect, leading to a higher α^*.

Innovation costs differ across industries. One stylized fact presented by Burk and Lemley (2009) is that patent protection is critical to innovation in pharmaceutical and biotechnology industries where the fixed cost of R&D is substantial, whereas it plays an insignificant role in information industry that appears to have relatively low fixed but high marginal cost of R&D. Our result is consistent with this empirical observation.

[17] Condition (11) is satisfied for all α, for instance, if $l(\alpha) = \tau\sqrt{\alpha}$.

5. CONCLUDING REMARKS

This paper has conducted a new analysis of patent policy in a framework of continual innovation. Greater patent strength expands the profit of the innovating firms against imitation, but also shifts profit from current to past innovators. While these two effects have been considered in various contexts in the literature, our approach allows us to combine them in a single model, to see their interactions clearly, and to show how their trade off depends on factors including the frequency, capability, and cost of innovation, as well as the competitive pressure from imitation.

By holding other things constant, we are able to identify and evaluate the impacts of individual industry characteristics on the relationship between innovation and patents. It is important to note, however, that the effects of patents on innovation in a particular industry are often determined jointly by several factors. For instance, while greater patent strength may stimulate R&D in innovative industries, higher marginal innovation cost and lower fixed innovation cost can make weaker patents in such an industry more conducive to innovation. Both the pharmaceutical industry and the IT industry may be considered as highly dependent on innovation for growth. According to Burk and Lemley (2009), however, patent protection is critical to innovation in the former but not in the latter. The different nature of innovation costs in the two industries could potentially explain the difference.[18] Thus, while different industries and/or countries may desire different patent strength to stimulate innovation , the proper formulation of patent policy will require careful considerations of multiple factors.

For tractability, we have studied a stylized model that abstracts from many other considerations. For instance, there may be more than one entrant competing for a new discovery

[18] In revisiting the patent paradox in the semiconductor industry in which there was a high patenting propensity even though it apppeared that patents were among the least effective mechanism for appropriating R&D returns, Hall and Ziedonis (2001) found that "...firms appear to be engaged in 'patent portfolio races' aimed at...negotiating access to external technologies on more favorable terms" (page 104). Bessen and Hunt (2007) obtained a similar finding by examining patenting behavior in software industry. These findings suggest that the profit division effect is important in these industries.

in the market; the incumbent, unlike being passive as in our model, may also actively innovate; innovation (ideas) may arrive randomly and can be implemented with some costs, as, for example, in O'Donoghue et al (1998) and Hunt (2004). While we expect that the qualitative nature of our results will continue to hold in more general settings, it would be desirable in future research to formally consider these and other potential extensions.[19]

Our theoretical results have potential empirical implications. For example, to the extent that frequent innovation is implied by a high discount factor in our dynamic model, our finding suggests that stronger patents stimulate R&D in countries with more frequent innovations; and, to the extent that capital-intensive industries have high fixed innovation costs, our finding also suggests that stronger patents stimulate R&D in more capital-intensive industries. While these are consistent with evidence from a number of existing cross-country and cross-industry studies, it would be interesting to develop new empirical studies in which these and other empirical implications of our analysis can be systematically evaluated.

APPENDIX

This appendix contains proofs for Propositions 1, 3, and 4.

Proof of Proposition 1. First, from (8), $\frac{\partial W}{\partial \alpha} \gtreqless 0$ when

$$\alpha \lesseqgtr 1 - \frac{\pi_\Sigma}{\pi'_\Sigma} + \frac{\delta}{1-\delta}\left[\lambda\phi + (1-\lambda\phi)\frac{\pi'_m}{\pi'_\Sigma}\right] \equiv F(\alpha, \delta). \tag{12}$$

Since

$$\frac{\partial^2 W}{\partial \alpha^2} = -\frac{2(1-\delta)\pi'_\Sigma}{1-\delta+2\delta\lambda\phi} + \frac{[(1-\delta)(1-\alpha)+\delta\lambda\phi]\pi''_\Sigma + \delta(1-\lambda\phi)\pi''_m}{1-\delta+2\delta\lambda\phi} < 0,$$

the solution of $\alpha = F(\alpha, \delta)$, if it exists, implies a maximum value of W. We investigate the

[19] For the purpose of this paper, we have studied the effects of patent protection on innovation and how this relationship varies with industry characteristics. It would be desirable in future research to further consider the welfare effects of patent policy.

situation where the solution of $\alpha = F(\alpha, \delta)$ lies in $[0,1]$.

Note that $\frac{\partial F}{\partial \delta} > 0$. Moreover, $F(\alpha, \delta) < 1$ if $\delta = 0$ and $F(\alpha, \delta) \to \infty$ if $\delta \to 1$. Since $F(\alpha, \delta)$ is continuous in $\delta \in (0,1)$, we can find a non-empty set $B(\alpha)$ such that, for any given $\alpha \in B(\alpha)$, there exists $\delta_\alpha \in (0,1)$ for which $F(\alpha, \delta_\alpha) = \alpha$. Define $\bar{\delta} = \max\{\delta_\alpha\} \in (0,1)$ .Then, if $\delta > \bar{\delta}$, for all $\alpha \in [0,1]$, we have $F(\alpha, \delta) > \alpha$, implying $\frac{\partial W}{\partial \alpha} > 0$.

Next, when $\delta = 0$, since $0 < 1 - \frac{\pi_\Sigma(0)}{\pi'_\Sigma(0)}$ and $\frac{\pi_\Sigma(\alpha)}{\pi'_\Sigma(\alpha)}$ increases in α, there exists a unique α^*, with $\alpha^* = F(\alpha^*, 0)$ such that $\alpha \lesseqqgtr F(\alpha, 0)$ when $\alpha \lesseqqgtr \alpha^*$, or $\frac{\partial W}{\partial \alpha} \gtreqqless 0$ when $\alpha \lesseqqgtr \alpha^*$.

Finally, for any $0 < \delta \leq \bar{\delta}$, there exists $\alpha^*(\delta) \in (0,1)$ that solves $\alpha = F(\alpha, \delta)$. Because $\frac{\partial^2 W}{\partial \alpha^2} < 0$, $\alpha^*(\delta)$ is unique and $\frac{\partial W}{\partial \alpha} \gtreqqless 0$ for $\alpha \lesseqqgtr \alpha^*(\delta)$. Moreover, since

$$\frac{\partial^2 W}{\partial \alpha \partial \delta} = \frac{(1 - \lambda\phi)\pi'_m + \lambda\phi 2\pi_\Sigma + \lambda\phi(2\alpha - 1)\pi'_\Sigma}{(2\delta\lambda\phi - \delta + 1)^2} > 0, \tag{13}$$

$\alpha^*(\delta)$ increases in δ. *Q.E.D.*

Proof of Proposition 3. When $l(\alpha) > 3\tau$, $\pi_m = l(\alpha) - \tau$, and $\pi_\Sigma = l(\alpha) + \Delta - \tau$. Thus, from (8),

$$(1 - \delta + 2\delta\phi)\frac{\partial W}{\partial \alpha} = -(1-\delta)[l(\alpha) + \Delta - \tau] + [1 - \alpha(1-\delta)]\, l'(\alpha). \tag{14}$$

Therefore, $\frac{\partial W}{\partial \alpha}$ increases in τ and W is concave with respect to α. It follows that α^* increases in τ.

When $l(\alpha) < 3\tau < l(\alpha) + \Delta$, $\pi_m = [l(\alpha) + \tau]^2 / (8\tau)$ and $\pi_\Sigma = l(\alpha) + \Delta - \tau$. Thus,

$$\begin{aligned} & (1 - \delta + 2\delta\phi)\frac{\partial W}{\partial \alpha} \\ = \; & -(1-\delta)[l(\alpha) + \Delta - \tau] + [(1-\delta)(1-\alpha) + \delta\phi]\, l'(\alpha) + \frac{\delta(1-\phi)[l(\alpha)+\tau]\, l'(\alpha)}{4\tau}. \end{aligned}$$

To show α^* increases (decreases), it suffices to show that $\frac{\partial W}{\partial \alpha}$ increases (decreases).

$\frac{\partial W}{\partial \alpha}$ increases in τ if

$$(1-\delta) - \frac{\delta(1-\phi)\, l(\alpha)\, l'(\alpha)}{4\tau^2} > (1-\delta) - \frac{\delta(1-\phi)\, 3\tau l'(\alpha)}{4\tau^2} \geq 0,$$

or $\delta \leq \frac{4\tau}{4\tau + 3(1-\phi)l'(\alpha)} \equiv \delta_1$. And, $\frac{\partial W}{\partial \alpha}$ decreases in τ if

$$(1-\delta) - \frac{\delta(1-\phi)\, l(\alpha)\, l'(\alpha)}{4\tau^2} < (1-\delta) - \frac{\delta(1-\phi)(3\tau - \Delta)\, l'(\alpha)}{4\tau^2} \leq 0,$$

or $\delta \geq \frac{4\tau^2}{4\tau^2 + (1-\phi)(3\tau-\Delta)l'(\alpha)} \equiv \delta_2 . Q.E.D.$

Proof of Proposition 4. (1) When $3\tau < l(\alpha)$, substituting $\pi_m = l(\alpha) - \tau$ and $\pi_\Sigma = l(\alpha) + \Delta - \tau$ into (10) and rearranging the terms, we obtain

$$\frac{3}{2}\delta c_1 (\phi^*)^2 + [c_1(1-\delta) - \delta\Delta]\,\phi^* = (1-\delta)(1-\alpha)[l(\alpha) + \Delta - \tau] + \delta[l(\alpha) - \tau + K]. \quad (15)$$

Therefore

$$\frac{\partial \phi^*}{\partial \alpha} = \frac{[(1-\delta)(1-\alpha) + \delta]\, l'(\alpha) - (1-\delta)[l(\alpha) + \Delta - \tau]}{3\delta c_1 \phi^* + c_1(1-\delta) - \delta\Delta}. \quad (16)$$

The innovation-maximizing patent protection, α^*, satisfies

$$[(1-\delta)(1-\alpha) + \delta]\, l'(\alpha) - (1-\delta)[l(\alpha) + \Delta - \tau] = 0,$$

which is independent of ϕ^*, c_1 and K. It follows that in this case $\partial\alpha^*/\partial c_1 = 0$ and $\partial\alpha^*/\partial K = 0$.

(2) When $l(\alpha) \leq 3\tau < l(\alpha) + \Delta$, we have $\pi_m = [l(\alpha) + \tau]^2 / (8\tau)$ and $\pi_\Sigma = l(\alpha) + \Delta - \tau$. Thus ϕ^* satisfies

$$\begin{aligned} & \frac{3}{2}\delta c_1 (\phi^*)^2 + \left[c_1(1-\delta) - \delta[l(\alpha) + \Delta - \tau] + \frac{\delta[l(\alpha)+\tau]^2}{8\tau}\right]\phi^* \\ = \; & (1-\delta)(1-\alpha)[l(\alpha) + \Delta - \tau] + \delta\left[K + \frac{[l(\alpha)+\tau]^2}{8\tau}\right]. \quad (17) \end{aligned}$$

Differentiating (17) with respect to α, we obtain the condition for α^*:

$$\left[(1-\delta)(1-\alpha)+\frac{\delta(l(\alpha)+\tau)+\delta\phi^*(3\tau-l(\alpha))}{4\tau}\right]l'(\alpha)-(1-\delta)[l(\alpha)+\Delta-\tau]=0. \quad (18)$$

Hence

$$\frac{\partial\alpha^*}{\partial c_1}=\frac{\frac{\partial\phi^*}{\partial c_1}\frac{\delta l'(\alpha^*)[3\tau-l(\alpha^*)]}{4\tau}}{\Omega}, \qquad \frac{\partial\alpha^*}{\partial K}=\frac{\frac{\partial\phi^*}{\partial K}\frac{\delta l'(\alpha^*)[3\tau-l(\alpha^*)]}{4\tau}}{\Omega},$$

where

$$\begin{aligned}\Omega &\equiv \left[2(1-\delta)+\frac{\delta(\phi^*-1)l'(\alpha^*)}{4\tau}\right]l'(\alpha^*)\\ &\quad -\left[(1-\delta)(1-\alpha^*)+\frac{\delta[l(\alpha^*)+\tau]}{4\tau}+\frac{\delta\phi^*[3\tau-l(\alpha^*)]}{4\tau}\right]l''(\alpha^*)\\ &> 0\end{aligned}$$

if

$$\frac{l''(\alpha^*)}{l'(\alpha^*)}<\frac{8(1-\delta)\tau+\delta(\phi^*-1)l'(\alpha^*)}{4(1-\delta)(1-\alpha^*)\tau+\delta[l(\alpha^*)+\tau]+\delta\phi^*[3\tau-l(\alpha^*)]},$$

which holds if (11) is satisfied.

Meanwhile, (17) implies

$$\frac{\partial\phi^*}{\partial c_1}=-\frac{\frac{3}{2}\delta(\phi^*)^2+(1-\delta)\phi^*}{3\delta c_1\phi^*+c_1(1-\delta)-\delta[l(\alpha)+\Delta-\tau]+\frac{\delta[l(\alpha)+\tau]^2}{8\tau}},$$

$$\frac{\partial\phi^*}{\partial K}=\frac{\delta}{3\delta c_1\phi^*+c_1(1-\delta)-\delta[l(\alpha)+\Delta-\tau]+\frac{\delta[l(\alpha)+\tau]^2}{8\tau}}.$$

But

$$
\begin{aligned}
& 3\delta c_1\phi^* + c_1(1-\delta) - \delta[l(\alpha)+\Delta-\tau] + \frac{\delta[l(\alpha)+\tau]^2}{8\tau} \\
> \ & \frac{3}{2}\delta c_1\phi^* + c_1(1-\delta) - \delta[l(\alpha)+\Delta-\tau] + \frac{\delta[l(\alpha)+\tau]^2}{8\tau} \\
= \ & \frac{(1-\delta)(1-\alpha)[l(\alpha)+\Delta-\tau] + \delta\left[F + \frac{[l(\alpha)+\tau]^2}{8\tau}\right]}{\phi^*} > 0,
\end{aligned}
$$

where the equality is due to (17). Thus $\frac{\partial\phi^*}{\partial c_1} < 0$ and $\frac{\partial\phi^*}{\partial K} > 0$. Furthermore, $\frac{\delta l'(\alpha^*)[3\tau - l(\alpha^*)]}{4\tau} > 0$. It follows that $\frac{\partial\alpha^*}{\partial c_1} < 0$ and $\frac{\partial\alpha^*}{\partial K} > 0$. *Q.E.D.*

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