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Strategic R&D Delays Generate Market Power

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Abstract

We develop a theoretical model in which both the R&D resources to develop new product applications and the market structure of consumption goods manufacturing are determined endogenously. There exists uncertainty with respect to the development date of an inaugural product, although higher R&D spending shortens the expected product development stage. Once an inaugural product application is introduced, the costs of imitation decline. According to the model, the time between a patent application and the development of an inaugural product is influenced by two factors: returns to scale in R&D and "strategic delays." Strategic delays in new product development are most likely to occur when earlier dates of new product development enable a larger number of imitators to penetrate an industry. In particular, we show that product developers tend to introduce new products later in the patent protection period when imitation costs are relatively low. We then explore the link between optimal patent lengths and market structure. Our findings suggest that, in order to minimize the strategic delay of inaugural applications, legal patent lengths should be shorter in industries where barriers to entry are relatively low.

Keywords: technological change, industrial organization, intellectual property, growth.

JEL Classification Numbers: I20, J24, O11, O31, O40.

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1. Introduction

Patent protection is an important pillar of the new growth theory. In a static framework, patent holders' ability to extract rents generates textbook inefficiencies due to deadweight loss, but in a dynamic growth model, the existence of such rents plays a key role in influencing R&D intensity, new product development, and technological progress.[1] An important extension of the endogenous growth literature highlights how industry market structure affects the patterns of economic growth. As papers in this strand demonstrate, endogenizing the market structure of consumption goods modifies and in some cases altogether alters the empirical implications of the new growth theory.[2]

While the conventional models of new growth theory accentuate the Schumpeterian roles of market size and patent protection in R&D intensity, the structure of markets that could emerge during the length of patent protection is also highly pertinent to the level of monopoly rents associated with R&D investments. In particular, product markets would be more competitive in nature so far as earlier dates of inaugural product development enable a larger number of imitators to more readily penetrate the industry.[3] This would suggest a natural but fundamental tradeoff: higher product development intensity subsequent to the approval of a patent would lead to not only earlier expected dates of product launch but also potentially more intense competition in the product markets and watered down returns to technological innovation. Due to this inherent tradeoff, the extent to which R&D intensity is utilized as a means to manipulate the product market structure could influence and perhaps dilute the impact of R&D investments on technological progress and economic growth.

In this paper, we develop a model in which both the R&D resources to develop new product applications and the market structure of consumption goods manufacturing are

[1] See, for example, Aghion and Howitt (1992, 1996) and Grossman and Helpman (1991a, 1991b).

[2] See, for instance, Aghion et al. (2004) and Peretto (1999a, 1999b).

[3] There are a number of economically plausible channels through which market entry becomes more feasible over time following the development and marketing of an inaugural product that utilizes a new technological innovation. These include–but are not confined to–learning-by-observation and reverse engineering. For related ideas and their roles in technological change, see Rosenberg (1982) and Mokyr (1990).

determined endogenously. There exists uncertainty with respect to the development date of an inaugural product, although higher R&D spending shortens the expected product development stage. Once an inaugural product application is introduced, the costs of imitation decline.

Using this framework, we are able to reach several novel conclusions. For instance, we find that the time between a patent application and the development of an inaugural product is influenced by two factors. First, if the marginal return to new product development is decreasing in the state of the existing technologies, then the length of time between a patent application and the development of new products would obviously and inevitably widen as technologies mature. In that case, reductions in the length of effective patent protection would be caused by "natural" delays due to diminishing returns to R&D. Second and more interestingly, in deciding how much to spend on new product development, patent holders would take into account the costs of imitation–and the inherent market structure commensurate with those costs–in deciding how much to spend on R&D. As a consequence, patent holders would adjust their product development efforts in an attempt to maximize their market power over the length of a patent. If indeed patentees reduce the investment in new product development based on such concerns, then the expected development date of an inaugural product would again be delayed. Thus, lower R&D intensity in product development based on such concerns would generate "strategic" delays. Naturally, strategic delays in new product development are most likely to occur when earlier dates of new product development enable a larger number of imitators to penetrate an industry. When that is the case, product developers would reduce their R&D intensity with the recognition that the sooner is the date of the inaugural product launch, the longer is the amount of time they face competition over the length of the patent. Taking into account both natural and strategic R&D delays, we show that the effective length of patents–the interval of time between the introduction of inaugural products and the expiration of patents–would be shorter when there exists decreasing returns to scale in R&D and imitation costs are relatively low.

Our model produces some strong normative repercussions as well. In particular, recognizing that there may be strategic delays in new product development drastically alters how changes in legal patent lengths could influence product development efforts as well as technological progress. For one, patent extensions may be growth enhancing if and only if strategic delays are of no major significance. That is, longer patents would unambiguously induce the patentees to raise their product development efforts only when the patentees are confident that the launch of a new product during an earlier stage of the patent protection period would generate sufficiently generous monopoly profits. This would be more likely when imitation is either costly or it takes a relatively long time. By contrast, extending the length of patents would not be growth enhancing in industries with lower barriers to entry (or in which imitation is swift). In such industries, extending the length of patents would generate lower profits for the innovator due to the fact that competition dilutes his or her monopoly rents. And in an attempt to limit the period over which the innovator shares its monopoly rents with the imitators, patentees would respond by reducing their product development efforts and generating strategic delays in product development in industries with low barriers to entry.[4]

A final implication of our model is that, based on the mechanisms we alluded to above, both the amount of product development investment made by patent holders and the expected number of imitators in goods production follow an inverted U-shape relationship in the length of patent licenses. The reason for this is that longer patents entice a higher number of imitators into an industry but, all else equal, they can induce the patent holder to lower her R&D investment as well. As a result of both these effects, equilibrium levels of R&D investment and the expected number of imitators first rise and then fall with longer patents. Indeed, other theoretical work as well as some detailed empirical analyses verify such non-monotonic relationships among R&D

[4] Implicit in this discussion is the fact that we shall abstract from the scope (or depth) of patent protection. In what follows we solely consider the duration of patent protection as the relevant policy tool, but an alternative to what we develop in this paper could include both the duration and the scope of patents as policy variables. In that case, and when adjusting the length of patents is not a desirable policy option, the latter could be utilized to raise entry barriers in industries in which strategic product development delays are considerable due to swift and easy imitation.

An alternative way to interpret our main findings then is to note that extensions of patent length would not necessarily generate the desired effects on product development efforts unless the former are also accompanied by modifications in patent scope.

spending, expected number of imitators and patent lengths.[5]

2. Related Literature

Our work is most related to Aghion et al. (2004) who first document that R&D in innovation reacts positively (negatively) to firm entry in technologically advanced (laggard) industries, and then proceed to develop a Schumpeterian growth model to backup this empirical finding. Their theoretical results are driven by the fact that, in technologically sophisticated industries, R&D firms can step up their innovative efforts to escape entry whereas, in technologically more mature industries, R&D firms cut back on R&D based on the recognition that they are at a competitive disadvantage vis-a-vis new entrants. The theory we develop below complements the work of Aghion et al. in three different dimensions. First, because we focus on product development based on existing and active patents–and not on innovations that could potentially generate new patents–we are able to address how the market structure of final goods production could be driven by deliberate R&D efforts. In contrast, Aghion et al. demonstrate that the threat of entry by one firm could motivate incumbents in technologically sophisticated industries to innovate in order to escape competition. Second, the focus on product development based on active patents (instead of innovations that could generate new patents) also highlights a complementary channel through which economic growth could be affected. That is, the threat of firm entry could not only spur or hamper new innovations (as in Aghion et al.) but it could also influence the speed with which patented ideas are converted to consumer products. And finally, taking the differential impact of firm entry on young and mature industries seriously, we proceed to examine how optimal patent lengths should be tailored to promote economic growth.

More broadly, this paper is related to three other strands that focus on patents and industrial organization. The first body of work to which our paper is related examines how R&D expenditures are influenced by patent lengths and time to expiration. For example, Kamien and Schwartz (1974) and Goel (1996) show that legal patent lengths

[5] For the related literature, see the Section 2.

and R&D spending are positively and monotonically related. In contrast, Horowitz and Lai (1996) emphasize the theoretical underpinnings of an inverse U-shape relationship between the rates of innovation and legal patent lengths and Lerner (2002) finds empirical support for such a non-monotonic relationship. In a similar vein, Dechenaux, Goldfarb, Shane and Thursby (2003) examine how the commercialization of ideas and the termination of licenses change with the age of patents. Their empirical findings verify that there exists an inverted U-shape relationship between the hazard rates of first commercial sale and the age of patents. They assert that this relationship attains due to two effects that go in opposite directions: the effective length of the patent license provides an incentive to the R&D firm that declines with time, but the probability of technical success increases every period as the firm raises its R&D investment. Ellison and Ellison (2000) examine whether the behavior of incumbent pharmaceutical companies change in periods close but prior to the expiration of patents. Their empirical findings support the conjecture that strategic intent to deter entry upon the expiration of patents is most pronounced in intermediate size markets (where, unlike small and large markets, both the willingness and ability to deter entry are significant). What we present below is related to this strand because we examine how the length of patent licenses influences R&D intensity. And like the efforts of Horowitz-Lai and Lerner, our model generates an inverted U-shape relationship between patent length and R&D investment. We differ from this line of work because we emphasize the endogeneity of the market structure in goods production as the source of the inverted-U shape relationship between R&D intensity and the legal patent length.

The second strand to which our work is related analyzes the influence of patent competition on R&D expenditure. In a very relevant piece, Weeds (2002) shows that the threat of a patent race can generate strategic delays in R&D investment (compared to single firm outcomes), particularly in symmetric and non-cooperative games. What we present below complements his findings because we show that market structure considerations could also generate strategic delays in R&D investment and technological progress.

The final body of work that is related to what we discuss here focuses on the role of imitation on patenting decisions. The most relevant example in this strand is Gallini (1992) where the imitation of a patented idea is costly and a rival's decision to imitate a patented idea depends on the length of patent protection: the longer the patent, the more likely it is that rivals will invent around a patented idea. The innovator's main decision is to whether to apply for a patent or keep her innovation as a trade secret. Using this model, Gallini shows that patent extensions need not necessarily generate more patent applications and revelations of new ideas. Due to the fact that longer patents make it even more likely that rivals will invent substitute products that lower the option value of a patent, the threat of imitation subsequent to a patent application lowers the incentives to reveal new ideas and raises those to keep them as trade secrets. Our paper differs from Gallini's work in two main respects. First, in Gallini's model, imitation is inevitable once a patent is filed (because filing a patent makes the new idea public knowledge). Hence, patent extensions have no effect on the decision to innovate. In our work, by contrast, the innovator can successfully block imitation through strategic delay. As a result, we find that patent extensions can have an impact on the pace of innovations. Second, endogenizing product development investment helps us to connect the literature on costly imitation and market structure with that of endogenous economic growth and technological change. By doing so, we are able to highlight not only the link between strategic R&D investments and endogenous growth but also identify optimal patent policies when some degree of imitation is inevitable.

The remainder of the paper is organized as follows: Section 3 describes our model. Section 4 discusses the product development process and establishes the optimal level R&D intensity in that process. Section 5 describes the market structure of consumption goods production that emerges in equilibrium. Section 6 concludes.

3. The Economy

Consider a closed economy with a fixed population N, $N > 0$, of identical households who supply their one unit of labor endowment inelastically. The production of consumption goods requires the input of labor only. The R&D industry is perfectly competitive and firms in this industry use a homogenous consumption good as their only input. When the discovery of a new idea is made, R&D firms apply for a patent that lasts L, $L > 0$, periods from the date of application.[6] Each new idea can serve as the basis of one new product variety and R&D firms need to spend resources to develop the inaugural product based on the latest idea. There is uncertainty with respect to the timing of the development of any new application, but higher R&D spending shortens the expected product development stage. Once the inaugural product is introduced, the costs of imitation decline and competitors can, with some time lag, develop imperfect substitutes for the inaugural product.

3.1 The Consumer

The representative household maximizes the lifetime utility

$$U_0 = \int_0^{\infty} \log u_t \exp(-\rho t) dt \qquad \text{where} \qquad \log u_t = \int_0^n \log \sum_m q^m x_{i,t} di \tag{1}$$

subject to the intertemporal budget constraint that the present discounted value of expenditure cannot be greater than then the present discounted value of wage income:

$$\int_0^{\infty} E_t dt \exp(-\rho t) dt \ \leq \ A \ + \ S \int_0^{\infty} w_t \exp(-\rho t) dt \ . \tag{2}$$

where

$$E_t \ = \ \int_0^n \left(\sum_m p_{i,t}^m x_{i,t} \right) di \tag{3}$$

In equation (1), $x_{i,t}$ represents the consumption of the ith variety of a differentiated product at time t, q^m is the quality associated with the ith variety, and n is the measure

[6]The competition in the R&D industry helps to ensure that applying for a patent immediately following the discovery of a potentially rewarding idea is the optimal choice. Extending our model to endogenize the timing of the patent application in a non-trivial fashion would leave our main qualitative results unchanged.

of differentiated products that hold value to consumers. In equations (2) and (3), E_t denotes the household's total expenditure on goods, A represents its wealth at time zero, S is its inelastic labor supply, and w_t is the wage income of the household at time t. By assumption, $\forall h$, $S \equiv 1$.

Following Grossman and Helpman (1991a, 1991b), the consumer's problem can be broken down into three stages: the allocation of life-time wealth across time; the allocation of spending across products at each instant; and the determination of expenditure on the available product quality levels at each instant. We now discuss each of these stages in turn working our way backwards.

In the final stage, households determine their expenditure on each product by choosing the quality level m that offers the lowest quality-adjusted price. That is, they choose the product variety i with the lowest $p^m_{i,t}/q^m$. Consumers are indifferent between quality level m and quality level $m-1$ if relative prices fully reflect the quality difference, i.e., $p^m_{i,t}/p^{m-1}_{i,t} = q$. We settle the indifference in favor of the higher quality level so the quality level selected is unique and only the highest quality level m sells in equilibrium.

In the second stage, consumers allocate evenly their expenditure across the unit measure of all products due to the fact that the elasticity of substitution between any two products is constant at unity. Letting $E_{i,t}$ denote the total expenditure of the household on variety i at time t, the demand for a product i with a quality level m equals $x^m_i = E_{i,t}/p^m_i$. As we noted above, the household does not demand products at other quality levels.

In the first stage, consumers evenly spread lifetime expenditure across time, $E_t = \sum_{i=0}^{n} E_{i,t} = E$, as the utility function for each consumer is time separable and the aggregate price does not vary across time. Thus, for a constant wage rate w, the demand for a product i with a quality level m, x^m_i, equals w/p^m_i.

3.2 Production

Production requires labor only. Any firm producing a consumption good of variety i requires a, $a > 0$, units of labor per unit of output. All known varieties of the differentiated products can be produced with a units of labor per unit of output.

Any firm producing a consumption good faces an inverse demand curve that takes the form $1/x_{i,t} = p_{i,t}$. The firm sets its price so that $(p_{i,t} - aw_t)/p_{i,t} = -1\ /[(\partial x_{i,t}/\partial p_{i,t})$ $(p_{i,t}/x_{i,t})]$. This is the standard monopoly pricing rule where the markup to price ratio is equal to inverse demand elasticity. Optimal pricing yields a manufacturing profit of v per consumer and total profits of Nv, $Nv \equiv V$.

3.3 Product Development Research

The legal patent length is L. The inventor of a new idea (that could be the basis of a new product with an underlying quality level q^m) can invest in the development of the first application of the new idea or license the product development process to some other firm.[7] We assume that there is uncertainty with respect to the development of an inaugural product, although the investment of resources to develop a new application helps to reduce the time interval between a patent application and the expected date of the introduction of an inaugural product.

Let d_t represent the level of product development investment of an R&D firm at time t. Also let $t_0(d_t, m)$ be the stochastic success date for developing the inaugural product when the underlying technology level equals m. Then the probability of developing an inaugural product at or before time t is, $\forall\ t \in [0, \infty)$,

$$\Pr[t_0(d_t, m) \leq t] = 1 - \exp[-h(d_t, m)t]. \tag{4}$$

[7] We take as given the underlying product quality level q^m and focus solely on the development of new products based on the innovation that generated the existing quality level q^m. This simplification could be justified if or when the cost of new product development is low relative to that of R&D for quality innovations. That would more likely be the case when a quality innovation is relatively new and only a few product varieties based on that innovation exist.

Of course, a more generalized and complete version of our model would endogenize R&D in quality innovations. We abstract from this extension for reasons of tracability, but if such an extension could be made, our model would also generate results similar to those in Gilbert and Newbery (1982) and Aghion et al. (2004). In both those papers new ideas or innovations are developed to escape competition.

It is also possible that a patent holder licenses its idea to be used by others to produce a product based on his or her patent. The main conclusions we discuss below would not be altered as long as licensees bid for the patent-holder's idea in a perfectly competitive fashion. In that case, all the rents associated with producing the good under the patent protection would still accrue to the patent holder.

Based on equation (4), the expected success date for the R&D firm is $1/h(d_t, m)$ where $h(d_t, m)$ is the hazard function in product development. By assumption, the hazard rate function $h(d_t, m)$ is such that the probability density function of new product development is strictly concave in d_t with $h_1 > 0$, $h_2 \leq 0$, $h_{12} \leq 0$, and $h_{12}h_2 - h_1h_{22} \geq 0$.[8]

In order to derive the expected profits of a product development firm, we need to first identify the expected number of imitators and the market structure that would emerge based on those imitators. To proceed, we assume that the patent holder for the original idea that underlies the latest product variety incurs a per-period opportunity cost c, $c > 0$, for each unit of the resources tied up in product development research. For all potential imitators, however, the cost of developing the substitutes for the inaugural product is prohibitively large. But after τ, $\tau > 0$, periods following the development of the first application based on the patent, the imitation cost declines to F, $F > 0$. Recalling that t_0 denotes the period in which the inaugural product hits the market, the total profits of the innovator drops to F in present value once imitation begins, which occurs in period t_1, $t_1 \equiv t_0 + \tau$.

The industry market structure is implicit in the imitation cost F and its lag τ. Given that the date of a new product development, t_0, is stochastic, the actual number of imitators that would emerge in a given industry, z_t, is also stochastic ex ante. But, once t_0 is realized, the level of entry in period t_1 will exhaust the present value of discounted profits. As a result, the following equilibrium condition will obtain:

$$\frac{V[\exp(-\rho t_1) - \exp(-\rho L)]}{\rho[1 + z(t_0)]} = F \tag{5}$$

[8] As we will discuss below, the strict concavity of the p.d.f. $f(d_t, m, t_0) \equiv h(d_t, m) \exp[-h(d_t, m) t_0]$ ensures that the equilibrium amount of product development investment is unique. The property $h_1 > 0$ captures the fact that the inter-temporal probability of a successful invention is increasing in product development effort d_t; $h_2 \leq 0$ covers both the case in which the inter-temporal probability of new product development effort is independent of the state of the technology (i.e. $h_2 = 0$) as well as the case in which it is decreasing in the state of the technology (i.e. $h_2 < 0$).

In addition, also note that the hazard rate specification we employ in our model is 'memoryless.' That is, the probability of developing the inaugural product on any given date t is only dependent on the R&D resources expended in that period. Our results are not dependent on this assumption either.

Solving equation (5), we get

$$z(t_0) = \max \left[0, \frac{V}{F\rho} \left[\exp(-\rho(t_0 + \tau)) - \exp(-\rho L) \right] - 1 \right] . \tag{6}$$

In Section 5, we discuss the market structure of consumption goods production in detail. For now, however, note that equation (5) implies that there is a date of discovery, $t_0 \leq L - \tau$, after which no imitator would choose to enter the industry. That is, if the inaugural product is introduced late enough, no imitator would find it profitable to enter given the imitation lag length τ. Letting T denote this date, setting the term on the right hand side of (5) equal to zero, and solving it for T yields

$$T = -\frac{1}{\rho} \log \left[\exp(-\rho L) + \frac{F\rho}{V} \right] - \tau. \tag{7}$$

According to (7), the threshold date of inaugural product development after which there is no imitation asymptotically approaches $L - \tau$ as the fixed cost of imitation F relative to the present value of aggregate profits V/ρ approaches zero. In that case and when the inaugural product is launched at or before $L - \tau$, imitators will emerge sometime during the patent protection period. Otherwise, the date T is sooner than L. This means that, if an inaugural product is introduced at or after the date T, $T < L - \tau$, there will be no imitators throughout the effective patent period $L - t_0$, where $L - t_0 \leq L - T$. In that case, the original product developer will enjoy its monopoly status as long as its patent protection lasts. In general, the higher the fixed cost of imitation relative to the present value of aggregate profits, the earlier the threshold product launch date T after which there will be no imitation (and the less severe will be the competition for the patentee during the remainder of the patent protection period). In any case, the expected duration of monopoly is either $t_1 - t_0 = \tau$ (if $t_0 < T$) or $L - t_0$ (if $t_0 \geq T$).

A patentee R&D firm proceeds by choosing the amount of development investment it plans to undertake in each period t, d_t. At any given time period t, such a firm has the following maximand:

$$\max_{d_t} \Pi(t) = \int_t^T \pi^C(t_0) h(d_t, m) \exp[-h(d_t, m) t_0] dt_0$$
$$+ \int_T^L \pi^N(t_0) h(d_t, m) \exp[-h(d_t, m) t_0] dt_0 \ , \tag{8}$$

where $\pi^C(t_0)$ and $\pi^N(t_0)$ respectively denote the expected present discounted value of introducing the inaugural product application before T and that of introducing it after T but before L. When $t_0 < T$, the product developer would face some competition prior to the expiration of her patent protection and when $T \leq t_0 < L$, she would not. Hence, we can express these conditional expected profit terms respectively as

$$\pi^C(t_0) = V \int_{t_0}^{t_1} \exp(-\rho s) ds + F - c \int_t^{t_0} d_t \exp(-\rho s) ds \ ; \qquad t_0 < T \ , \tag{9}$$

$$\pi^N(t_0) = V \int_{t_0}^{L} \exp(-\rho s) ds - c \int_t^{t_0} d_t \exp(-\rho s) ds \ ; \qquad T \leq t_0 < L \ . \tag{10}$$

Clearly, the expected profits of a product developer, given by equations (8) through (10), could be influenced by many factors, but the market structure that would emerge once the imitators begin to market variants of the inaugural product is of utmost importance. The extent of imitation in each industry is in turn determined by the barriers to entry.

4. Equilibrium Product Development Effort

The problem of the patent holder is to maximize equation (8) with respect to the product development effort d_t, taking as given equations (4), (7), (9), (10) and the state of the

R&D technology m. The first-order condition for this problem satisfies

$$\left.\begin{array}{r}\int_t^T \pi^C(t_0)\,[1-h(d_t,m)t_0]\,h_1 \exp[-h(d_t,m)t_0]dt_0 \\ +\int_T^L \pi^N(t_0)\,[1-h(d_t,m)t_0]\,h_1 \exp[-h(d_t,m)t_0]dt_0 \\ +\int_t^T h(d_t,m)\exp[-h(d_t,m)t_0]\frac{\partial \pi^C(t_0)}{\partial d_t}dt_0 \\ +\int_T^L h(d_t,m)\exp[-h(d_t,m)t_0]\frac{\partial \pi^N(t_0)}{\partial d_t}dt_0\end{array}\right\} \leq 0 \tag{11}$$

where

$$\frac{\partial \pi^C(t_0)}{\partial d_t} = \frac{\partial \pi^N(t_0)}{\partial d_t} = -c\int_t^{t_0} \exp(-\rho s)ds < 0\ . \tag{12}$$

The first two terms in equation (11) define the benefit of a marginal increase in product development effort and the last two terms define its cost. The marginal benefit of product development effort represents the increase in expected profits due to an increase in d_t. According to those first two terms in (11), an increase in d_t helps to prolong the effective patent length, $L - t_0$, and extends the time period over which the patent holder can exercise some degree of market power. The marginal cost of product development is given by the last two terms in (11) and equation (12). The optimal level of product development investment given by (11) and (12) is, of course, dependent on the current time period t. The next proposition summarizes this observation.

Proposition 1 *The profit-maximizing product development investment, d_t^*,*

(i) *is strictly decreasing in t when $F > F_1$ and it is strictly increasing in t when $F \leqslant F_1$;*

(ii) *attains an interior maximum and has an inverted U-shape with respect to t.*

Proof: See Appendix Section A.1.

Proposition 1 indicates, for a given level of imitation cost F, the incentive to develop a new product first rises and then falls as the expiration date approaches. When there is a sufficiently long time to expiration, product developers have no incentive to rush since launching the product at an earlier date would entice more competition. However, as the patent expiration date nears, the threat from imitation declines but so does the monopoly rent associated with the product launch. These two conflicting forces generate a peak in product development investment sometime during the patent protection period where the peak is associated with an expected product launch date that delays imitative entry and yields relatively more monopoly power.

At this point, it is important to note that the marginal benefit of increasing the product development effort depends on the ease of imitation in–and entry into–the product market. As equations (8)-(10) show, the innovator either enjoys being the sole monopolist of this product for a longer period of time or shares the monopoly rents with only a very restricted number of firms when imitation is rather difficult (i.e., when either τ is large, F is large or both). By contrast, when imitation is relatively easier (when both τ and F are relatively small), the innovator's monopoly rents get diluted sooner and more severely. As it will become apparent below, most of our main results are related to this observation.

Proposition 2 *The profit-maximizing product development investment, d_t^*, is strictly increasing in*

(i) *the imitation cost F;*

(ii) *the imitation lag τ.*

Proof: See Appendix Section A.2.

Both returns to scale in product development and the market structure that eventually emerges play important roles in determining the intensity of product development.

Together, they influence the extent to which product development is delayed and the length of effective patent protection changes over time. In particular, there are two potential sources of delay in product development according to this framework: one, to the extent that the marginal product of development effort is decreasing in the underlying level of technology, there is a "natural delay" over time in new product development.[9] Put differently, as technologies become more sophisticated and the expected odds of success in developing a new product decline, the equilibrium amount of development effort decreases. Two, to the extent that imitation dilutes monopoly rents, there exists some "strategic delay." That is, the ease with which imitators can enter the market is important because developers take into account how their expected timing of success influences the competition they face in the future. And as Proposition 2 indicates, in industries in which imitation is not prohibitively costly and time consuming (following the emergence of an inaugural product), the benefit of delaying product development so as to ensure pure monopolistic rents over a relatively longer segment of the effective patent protection period can be significant.

When $h_2 = 0$ so that the marginal success rate of developing new products depends only on R&D intensity and not on the state of the underlying level of technology, the problem that patent holders face and the optimal product development effort that emerges as the solution is invariant to the quality of the product i. According to Proposition 2 and the first-order conditions given by (11) and (12), there are three main determinants of the equilibrium product development effort d_t^*. They are the length of the patent period L; the cost of imitation F; and imitation lag τ. All of these three parameters help to determine the number of firms, z_t, in the production of variety i with the underlying technology level m. Not surprisingly, the optimal product development effort will be higher in industries where either imitation costs or its time lag is high enough to restrict the potential number of entrants. Put differently, as long as the imitation cost is prohibitively high or it takes a relatively long period of time to imitate, a patent holder will have all the incentives to develop the ith variety as soon as possible because her monopoly profits would not be diluted once she is successful.

[9] This is the case when $h_2 < 0$.

In contrast, when $h_2 < 0$ so that the marginal success rate of developing new products also depends negatively on the state of the underlying level of technology, the equilibrium amount of effort, d_t, will adjust with changes in the underlying technology level. As it becomes more and more difficult to develop new products, the expected return to product development effort will decline with improvements in the level of technology. Moreover, the delay in the introduction of inaugural products and the rate at which the effective length of patents, $L - t_0$, decreases will depend on the ease of imitation in that industry–and the market structure of goods production commensurate with it. That is, the interaction between natural delay as a result of decreasing returns to product development and strategic delay due to market structure considerations will influence the degree to which the effective patent lengths narrow as technologies become more sophisticated.

Proposition 3 *The profit-maximizing product development investment, d_t, is strictly decreasing in the underlying level of technology, m, when $h_2 < 0$, $h_{12} \leqslant 0$, and $h_{12}h < h_1 h_2$.*

Proof: See Appendix Section A.3.

When the marginal return to product development is decreasing in the state of the existing technologies, patent extensions may be growth enhancing if and only if strategic delays are of no major significance. Put differently, longer patents would induce patentees to raise their product development efforts only when the discovery of a new product during an earlier stage of the patent protection period generates a longer interval of time during which the innovator enjoys either all of the monopolistic rents or–if there is imitation early on–close to all of the monopolistic rents (because there are only a few imitators). That, of course, would be the case in industries with high entry barriers (i.e., where F or τ is high). By contrast, we find that longer patents would not be growth enhancing in industries with lower entry barriers. In these industries, holding constant the development date of an inaugural product, longer patents would just prolong the time period during which the innovator draws much-diluted rents due to fierce competition. Hence, in industries with low entry barriers (i.e. where F and τ are low), patentees would respond by reducing their product development efforts and by strategically delaying the development of their product. In sum, we find that patent extensions are more effective in industries with high entry barriers.

Proposition 4 *For the profit maximizing innovator,*

(i) d_t^* *is strictly increasing in the legal patent length, L, when the imitation cost is relatively high ($\forall\ F > F_1$) and strictly decreasing in the legal patent length, L, when the imitation cost is relatively low ($\forall\ F < F_1$);*

(ii) d_t^* *has an inverted U-shape with respect to the legal patent length, L, when there is imitation;*

(iii) *the skewness of this curve rises with the imitation lag, τ.*

Proof: See Appendix Section A.4.

A corollary of the above discussion is that, for given combinations of imitation cost F and time lag τ, the equilibrium amount of product development intensity would first rise and then fall with extensions in patent lengths. Figure 1 depicts this result.

[Figure 1 about here.]

In Figure 2.a, we plot the relationship between the current time period t and the expected duration of monopoly relative to the length of the effective patent period, $L - t_0$. In the figure, we denote the expected duration of monopoly by mon, which either equals $t_1 - t_0 = \tau$ if $t_0 < T$ or $L - t_0$ if $t_0 \geq T$. As shown, the further we get into the monopoly protection period and the inaugural product is not yet developed, the lower is product development spending, d_t, and the longer is the period of monopoly the original product developer will enjoy relative to the effective patent protection period $L - t_0$. Of course, if the inaugural product is developed at or after date T, all imitators will be deterred from entry and the original product developer will enjoy monopoly throughout the remainder of the patent protection period. The dashed line in Figure 2.a depicts the impact of lower product development spending, d_t, on the duration of monopoly during the patent protection period. As shown, one effect of lower product development spending is to extend the duration of monopoly relative to the remaining (or effective) protection period. In Figure 2.b, we show how changes in patent length influence the expected duration of monopoly relative to the length of the effective patent period, $L - t_0$. The solid line shows the benchmark case in which we hold constant the initial optimal product development investment. The dashed line also incorporates the adjustments in the optimal level of product development investment. As shown, strategic delays in product development kick in at longer patent lengths. That the dashed line lies above the solid line is indicative of the fact that strategic delays are at play for longer patents.

[Figures 2.a and 2.b about here.]

5. The Production Market Structure

Recall that, since the date of a new product development, t_0, is stochastic, the actual number of imitators that would emerge in a given industry, z_t, is also stochastic. Still, in an ex ante sense, more can be said about the degree of competition that could emerge in each industry and the factors that would influence this competition.

In expected terms, the potential number of entrants given by equation (6) can be defined as

$$E_t\left[z(t_0)\right] = \int_t^T z(t_0) h(d_t, m) \exp[-h(d_t, m) t_0] dt_0. \tag{13}$$

We are able to make a number of observations with regard to the structure of markets that emerge subsequent to the development of inaugural products.

The equilibrium number of expected imitators, $E_t[z(t_0)]$, rises with the product development investment, d_t, as described in Lemma 1 below. The underlying reason is fairly evident: a higher development effort by the innovator would lead to an earlier expected date of success in developing this inaugural product, thereby attracting more imitators to free ride this success. Such free-ride incentives would be smaller in industries with relatively high barriers to entry. This in turn would suggest that higher development efforts would draw fewer imitators into the product markets in industries with high entry barriers.

Lemma 1 *The expected equilibrium number of imitators, $E_t[z(t_0)]$, is strictly increasing in product development investment, d_t.*

Proof: See Appendix Section A.5.

The impact of entry barriers, F, on the equilibrium number of imitators, $E_t[z(t_0)]$, consists of two factors–one that is *direct* and the other that is *indirect*. Entry barriers reduce the number of imitators directly by making imitation more costly. At the same time, however, they bring forward the expected date of inaugural product development. This is due to the fact that higher barriers to entry prolong innovator's effective patent protection and entice her to invest more in product development. The overall impact of changes in F on the market structure of the consumption good production, therefore, depends on which of the above two factors dominates. This finding is addressed formally in our next proposition.

Proposition 5 *The expected market structure of consumption goods production, $E_t[z(t_0)]$,*

(i) *falls with more entry barriers, F, if the direct effect of F on discouraging imitation dominates;*

(ii) *rises with more entry barriers, F, if the indirect effect of F on encouraging product development investment–and therefore attracting more imitation–dominates.*

Proof: See Appendix Section A.6.

The legal patent length also influences the number of imitators in the market. On the one hand, a longer patent length allows imitators to enjoy some degree of imperfect competition for an extended period of time thereby engendering more imitation. This is the *direct* effect of longer patents on imitation. On the other hand, a longer patent generates an *indirect* effect through the equilibrium level of product development investment. This is due to the fact that longer patents encourage more product development investment in industries with sufficiently high entry barriers; lead to an increase in product development investment by innovators; bring forward the expected date of the inaugural product development; and induce more imitators to free ride such efforts. In this case, both the direct and indirect forces affect the market structure in the same direction and we conclude that patent extensions would raise the number of imitators when barriers to entry are sufficiently high (i.e., when $F \geqslant F_2$). However, when barriers to entry are significantly low (i.e., when $F << F_2$), extending patent lengths would only discourage the equilibrium product development effort and reduce the probability of a free ride. In general, if the indirect effect dominates, the number of imitators would decrease when the legal patent length is extended.

Proposition 6 *The expected market structure of consumption goods production, $E_t[z(t_0)]$,*

(i) *rises with a longer legal patent length, when the imitation cost exceeds a certain level, F_2; falls with a longer legal patent length, when the imitation cost is sufficiently lower than F_2.*

(ii) *has an inverted U-shape with respect to the legal patent length, L, when there is imitation.*

Proof: See Appendix Section A.7.

An implication of this proposition is that, for any given level of imitation cost F and imitation lag τ, the expected number of imitators would first rise and then fall with extensions in patent lengths. Figure 3 depicts this result.

[Figure 3 about here.]

In Figure 4, we summarize the policy implications of our main conclusions. In industries where imitation is relatively easy and costless, there will be imitation and strategic delays in R&D investment in equilibrium. Over a broader range of L, extending the length of patents in such industries would lead to lower R&D investment and even greater delays in product development. In contrast, in industries where imitation is more difficult and costly, there will be no imitation or delays in R&D investment in equilibrium as long as the length of patent licenses, L, is sufficiently short. Over a broader range of L, patent extensions would lead to higher R&D investment and even shorter delays in product development in such industries. For any given level of imitation cost F, the growth-enhancing level of optimal patent length L would be the one at the upper bound of region II in Figure 4. Thus, the higher is the cost of imitation, the longer is optimal patent protection.

[Figure 4 about here.]

6. Conclusion

The novelty of the theoretical model we developed above is that both the R&D resources to discover new product applications and the market structure of consumption goods manufacturing are determined endogenously. There exists uncertainty with respect to the development date of an inaugural product, although higher R&D spending shortens the expected product development stage. Once an inaugural product application is introduced, the costs of imitation decline.

On the basis of this model, we are able to reach several important conclusions. First, the time between a patent application and the development of an inaugural product is influenced by two factors. On the one hand, if the marginal return to new product development is decreasing in the state of the existing technologies, then reductions in the length of effective patent protection are caused by “natural” delays. On the other hand, in deciding how much to spend on new product development, patent holders take into account how imitation costs influence the degree of product market competition once an inaugural product hits the market. If imitation is relatively easy, then there are “strategic” delays in new product launches due to the fact that patent holders invest less in product development. Taking into account these two factors, the effective length of patents would be shorter when there exists decreasing returns to scale in R&D and imitation costs are relatively low.

Second, when there are potential strategic delays in new product development, changes in the length of patent protection could influence product development intensity as well as the pace of economic growth in different ways. When the marginal return to product development is decreasing in the state of the existing technologies, patent extensions may be growth enhancing if and only if strategic delays are not prevalent. By contrast, extending the length of patents would not be growth enhancing in industries with lower entry barriers. In such industries, holding constant the development date of an inaugural product, lengthier patents would draw a significant level of additional competition. And in an attempt to keep stable the period over which they enjoy a pure monopoly status, patentees would respond by reducing their product development efforts–and, hence, by strategically delaying the anticipated development date of their product.

7. Appendix

A.1 Proposition 1: The profit-maximizing product development investment, d_t^*,

(i) is strictly decreasing in t when $F > F_1$ and it is strictly increasing in t when $F \leqslant F_1$;

(ii) attains an interior maximum and has an inverted U-shape with respect to t.

Proof: (i) When $d_t = 0$ (and hence $h(d_t, m) = 0$), the first-order condition (denoted as FOC) can be simplified as

$$\left\{ \begin{array}{c} \{V[-\exp(L\rho) + \exp(\rho(L+\tau)) - \exp(\rho(t+\tau))\rho(L-T)] \\ -F\rho\gamma[1+\rho(T-t)]\}h_1(0,m) \end{array} \right\} \Big/ \gamma\rho^2 \quad > \quad 0, \tag{a.1}$$

where $\gamma \equiv \exp[\rho(L+t+\tau)]$ and, due to the fact that $\rho(L-T) < 1$, $t < L$, we have $|\rho\ (T-\ t\ )| < 1$, and $h_1(0,m) > 0$.

When $h_1 \to 0$, the first-order condition is

$$\frac{\exp[-(L+t)(\rho+h)]\{-\exp[L(\rho+h)]\rho + \exp(th)[-\exp(t\rho)h + \exp(L\rho)(\rho+h)]\}}{\rho(\rho+h)}. \tag{a.2}$$

The first-order condition specified in (a.2) is negative only if $-\exp[L(\rho+h)]\rho + \exp(th)[-\exp(t\rho)h + \exp(L\rho)(\rho+h)] < 0$, the derivative of which with respect to t is equal to $h(h+\rho)[\exp(L\rho+th) - \exp(t\rho+th)] > 0$ because $t < L$. When $t = L$, the first-order condition in (a.2) is 0. Thus, $(a.2)$ is negative $\forall t < L$.

Next we note that the profit function $\Pi(t)$ is continuous and strictly concave in d_t and that the support of d_t is closed and bounded from below and above at 0 and V/ρ respectively. Thus, the function Π_t attains a unique maximum. Together with equations (a.1) and (a.2), we can verify that the solution to this maximization is interior. As a consequence, we establish that $\partial FOC/\partial d_t$, evaluated at the optimal level of d_t, is strictly negative.

According to the implicit function theorem, the sign of $\partial d_t/\partial t$ depends on $\partial FOC/\partial d_t$, where

$$\frac{\partial FOC}{\partial t} = \frac{\exp[-\rho(t+\tau)-h(L+t)]}{\rho}\left\{\begin{array}{l}\exp(\rho\tau)[\exp(Lh)-\exp(th)]\rho \\ + \\ [\exp(Lh)V-\exp(\rho(t+\tau)+Lh)F\rho \\ + \\ \exp(\rho\tau+th)Ld_t\rho-\exp(\rho\tau+Lh)(V+d_t t\rho) \\ + \\ \exp(Lh)t[(\exp(\rho\tau)-1)V+\exp(\rho(t+\tau))F\rho]h]h_1\end{array}\right\} \tag{a.3}$$

Furthermore, we find that

$$\frac{\partial^2 FOC}{\partial t\partial F} = -h_1\exp(-th)(1-th)<0 \tag{a.4}$$

because at each t the expected success date $(1/h)$ is later than or equal to t, i.e., $1-ht > 0$ at t and $h_1>0$. Denote F_1 as the unique solution that sets equation (a.3) equal to 0. $\forall F>F_1$, $\partial FOC/\partial t<0$ and $\forall F\leqslant F_1$, $\partial FOC/\partial t\geqslant 0$.

(ii) When $t=0$, $\partial FOC/\partial t = 1-\exp(-Lh)+[\exp(-Lh)Ld_t-F-\tau V]h_1 > 0$ because $F+\tau V<\exp(-Lh)Ld_t$ which approximately ensures the break-even d_t is reached at $t<L$. When $t=L$, τ and F are no longer relevant and, since $1/h<L$, we have $\partial FOC/\partial t = -[h_1(Lh-1)V] \,/\, \rho\delta<0$, where $\delta\equiv\exp[L(\rho+h)]$. Next we note that the FOC is continuous in t and that the support of t is closed and bounded from below and above at 0 and L respectively. Thus, the function FOC attains a maximum where $\partial FOC/\partial t=0$ and the solution to this maximization is interior. As a result, $\partial^2FOC/\partial t^2$, evaluated at the optimal level of t, is strictly negative and $\partial d_t^*/\partial t = -[\partial FOC/\partial t]/SOC$, where SOC (the second-order condition) at d_t^* is strictly negative as established in (i). Hence, the sign of $\partial d_t^*/\partial t$ is consistent with the sign of $\partial FOC/\partial t$. According to the uniqueness and existence theorem, a unique t that sets $\partial FOC/\partial t$ equal to zero can be ensured for $\rho \in [\rho',\, \rho'']$ where $\rho' > 0$ and $\rho'' < V/F$. So d_t^* also attains an interior maximum with respect to t and exhibits an inverted U-shape. ■

A.2 Proposition 2: The profit-maximizing product development investment, d_t^*, is strictly increasing in

(i) the imitation cost, F;

(ii) the imitation lag, τ.

Proof: (i) According to the implicit function theorem, the sign of $\partial d_t/\partial F$ depends on $\partial FOC/\partial F$ where FOC denotes the first-order condition:

$$\frac{\partial FOC}{\partial F} = h_1 \exp(-th)\{\exp[h(t-T)]T - t\}, \tag{a.5}$$

where $h_1 > 0$. Taking the derivative of $\exp[h(t-T)]T - t$ with respect to t, we get $Th\exp[(t-T)h] - 1 < 0$ for $t < T$. Because the rest of the argument also falls with a larger t, the $\partial^2 FOC/\partial F \partial t < 0$ for $t < T$. and we find that $\partial FOC/\partial F$ is equal to 0 when $t = T$ and when $t > T$ (the latter is true because F becomes no longer relevant). Thus, we conclude that $\partial FOC/\partial F > 0$ and $\partial d_t/\partial F > 0$ for any $t < T$. The equilibrium product development effort, d_t^*, is strictly increasing in the imitation cost, F, $\forall\ t < T$.

(ii) Likewise,

$$\begin{aligned}\frac{\partial FOC}{\partial \tau} &= \frac{h_1 \exp[-(L+t)(\rho+h) - \rho\tau]}{\rho[\rho+h]^2}\{-\delta V\rho[th(\rho+h) - \rho] \\ &\quad - \exp[-(T+\tau)h]\rho[\exp[\rho(t+\tau)]\eta V + \gamma\eta F\rho][\rho - Th(\rho+h)]\}\end{aligned} \tag{a.6}$$

where $h_1 > 0$ and where $\eta \equiv \exp[h(L+t+\tau)]$. Taking the derivative of the term within the grand brackets with respect to t, we get $\rho(\rho+h)\{-Vh\delta - \exp(Lh)V[\rho - Th\rho - Th^2] < 0$ when $t = T$, because $Th < 1$ and $\delta > \exp(Lh)$. For the rest of the arguments in (a.6), the negative correlation with t holds as well. Hence, $\partial^2 FOC/\partial\tau\partial t < 0$ when $t = T$. Furthermore, when $t = T$ or when $t > T$, $\partial FOC/\partial\tau = 0$. Thus, $\partial FOC/\partial\tau > 0$ and $\partial d_t^*/\partial\tau > 0\ \forall t < T$. The equilibrium product development effort, d_t^*, is strictly increasing in the imitation lag, τ, $\forall t < T$. ■

A.3 Proposition 3: The profit-maximizing product development investment, d_t^*, is strictly decreasing in the underlying level of technology, m, when $h_2 < 0$, $h_{12} \leqslant 0$, and $h_{12}h < h_1 h_2$.

Proof: In equations (9) and (10), $\pi^C(t_0)$ and $\pi^N(t_0)$ are independent of m. Denote $f(d_t, m, t_0) \equiv h(d_t, m)\exp[-h(d_t, m)t_0]$, and $\alpha \equiv f(d_t, m_2, t_0)\ /\ f(d_t, m_1, t_0)$ where $m_2 > m_1$. We find that $\alpha \leqslant 1$, because

$$\frac{\partial\{h(d_t, m)\exp[-h(d_t, m)t_0]\}}{\partial m} = h_2 \exp[-h(d_t, m)t_0](1 - ht_0) < 0\ , \tag{a.7}$$

which holds due to the fact that, at each date t, the expected success date $(1/h)$ is later than or equal to t, i.e., $1 - ht > 0$ at t.

When $m = m_i$, the first-order condition can be written as

$$\begin{aligned}\frac{d\Pi(d_t, m_i)}{dd_t} &= \int_t^T \left[\frac{d\pi^C(t_0)}{dd_t} f(d_t, m_i, t_0) + \pi^C(t_0)\frac{df(.)}{dd_t}\right] dt_0 \\ &\quad + \int_T^L \left[\frac{d\pi^N(t_0)}{dd_t} f(d_t, m_i, t_0) + \pi^N(t_0)\frac{df(.)}{dd_t}\right] dt_0.\end{aligned} \tag{a.8}$$

Given $f(d_t, m_2, t_0) = \alpha f(d_t, m_1, t_0)$, we obtain

$$\begin{aligned}\frac{d\Pi(d_t, m_2)}{dd_t} &= \int_t^T \left[\alpha\left[\frac{d\pi^C(t_0)}{dd_t} f(d_t, m_1, t_0) + \pi^C(t_0)\frac{df(.)}{dd_t}\right] + \pi^C(t_0) f(d_t, m_1, t_0)\frac{d\alpha}{dd_t}\right] dt_0 \\ &\quad + \int_T^L \left[\alpha\left[\frac{d\pi^N(t_0)}{dd_t} f(d_t, m_1, t_0) + \pi^N(t_0)\frac{df(.)}{dd_t}\right] + \pi^N(t_0) f(d_t, m_1, t_0)\frac{d\alpha}{dd_t}\right] dt_0.\end{aligned} \tag{a.9}$$

where

$$\frac{d\alpha}{dd_t} = \exp[-h(m_2)t_0 - h(m_1)t_0]\{h_1(m_2)[1 - h(m_2)t_0]h(m_1)$$
$$-h_1(m_1)[1 - h(m_1)t_0]h(m_2)\}. \tag{a.10}$$

According to (a.10), $d\alpha/dd_t < 0$ if and only if $h_1(m_2)[1 - h(m_2)t_0] \ / \ h(m_2) < h_1(m_1)[1 - h(m_1)t_0] \ / \ h(m_1)$. Note that $\partial\{h_1(m)[1 - h(m)t_0]/h(m)\} \ / \ \partial m = \{(1 - ht_0)[h_{12}h - h_1h_2] - h_1h_2t_0h\} \ / \ h^2 < 0 \Rightarrow d\alpha/dd_t < 0$ if $h_{12}h < h_1h_2$ (which would imply that $h_{12}h < h_1h_2/(1 - ht_0)$ because $h_1h_2 < h_1h_2/(1 - ht_0)$). When $d\Pi(d_t^*, m_1)/dd_t^* = 0$, equation (a.8) is equal to zero. Then comparing equation (a.9) with equation (a.8), we conclude that $d\Pi(d_t^*, m_2)/dd_t^* < 0$ when $d\Pi(d_t^*, m_1)/dd_t^* = 0$, given that $i = 1$, $\alpha \leqslant 1$, and $d\alpha/dd_t < 0$. These indicate that higher d_t^* shifts the integrand downward. Hence, the profit-maximizing d_t^* is strictly decreasing in the underlying level of technology, m.

■

A.4 Proposition 4: When the innovator maximizes their profit,

(i) d_t^* is strictly increasing in the legal patent length, L, when the imitation cost is relatively high ($\forall \ F > F_2$) and strictly decreasing in the legal patent length, L, when the imitation cost is relatively low ($\forall \ F < F_2$);

(ii) d_t^* has an inverted U-shape with respect to the legal patent length, L, when there is imitation;

(iii) the skewness of this curve rises with the imitation lag, τ.

Proof: (i) According to the implicit functional theorem, the sign of $\partial d_t^*/\partial L$ depends on $\partial FOC/\partial L$ given that $\partial FOC/\partial d_t^* < 0$.

$$\frac{\partial FOC}{\partial L} = \frac{\exp[-(L+t)\rho - Lh]}{\rho}\{h_1[-d_t^* \exp(L\rho) + \exp(t\rho)(d_t^* + LV\rho)$$

$$- V\rho T \exp(t\rho + h(L-T))] + h[(\exp(L\rho) - \exp(t\rho))(Ld_t^* h_1 - 1)]\}, \quad \text{(a.11)}$$

where T is defined by equation (7). Denote F_2 as the unique solution that sets equation (a.11) to 0. Then note that

$$\frac{\partial(\partial FOC/\partial L)}{\partial F} = \frac{\exp[-Th]V[1-hT]}{V + \exp(L\rho)F\rho} > 0, \quad \text{(a.12)}$$

because, $hT < 1$, which in turn implies that $\forall\ F > F_2$, $\partial FOC/\partial L > 0$ and $\partial d_t^*/\partial L > 0$. Consequently, d_t^* is an increasing function of the length of patent protection L when the entry barriers are sufficiently high. In contrast, $\forall\ F < F_2$, $\partial FOC/\partial L < 0$ and thus $\partial d_t^*/\partial L < 0$. This implies that d_t^* is a decreasing function of the length of patent protection L when the entry barriers against imitators are sufficiently low.

(ii) Note that when $L = 0$, T approaches $-\infty$, t and τ are limited to zero, and $\partial FOC/\partial L = -\exp[-h(T+\tau)]V(T+\tau)h_1$ which approaches $+\infty$. When $L = T + \tau$, $\partial FOC/\partial L = \exp[-\rho(T+\tau+t) - (T+\tau)h]/\rho\ \{h_1\ [-\exp[(T+\tau)\rho]d_t^* + \exp(t\rho)\ [d_t^* + (T+\tau)V\rho] - \exp(t\rho + \tau h)\ V\rho T] + [\exp[(T+\tau)\rho] - \exp(t\rho)]\ h[d_t^*(T+\tau)h_1 - 1]\ \} < 0$. Similar to A.1, we find that the FOC and thus d_t^* reach a maximum with respect to L, and d_t^* has an inverted U-shape with respect to L.

(iii) Because

$$\frac{\partial FOC}{\partial L \partial \tau} = \exp[-L\rho - hT]V[1-hT] > 0, \quad \text{(a.13)}$$

F_2 is an increasing function of τ, and thus the curve that relates d_t^* and L is thus more skewed to the right (i.e., the range over which $F > F_2$ is enlarged) when τ rises. ■

A.5 Lemma 1: The expected market structure of consumption goods production, $E_t\left[z(t_0)\right]+1$, is strictly increasing in the innovator's product development investment, d_t^*.

Proof: The market structure of consumption goods production can be explicitly written as:

$$z(t_0)+1=\frac{\exp[-\rho(L+t_0+\tau][\exp(L\rho)-\exp(\rho(t_0+\tau))]V}{F\rho}, \tag{a.15}$$

which is a decreasing function of t_0.

Taking the expectation of (a.15) as in equation (13), we get

$$E[z(t_0)+1]=\int_t^T [[z(t_0)+1]h(d_t,m)\exp[-h(d_t,m)t_0]]\,dt_0, \tag{a.16}$$

where the density function $f(d_t,m,t_0)\equiv h(d_t,m)\exp[-h(d_t,m)t_0]$ is a strictly increasing function of d_t when $t_0<(1/h)$ but a decreasing function of d_t when $t_0\geqslant(1/h)$. A larger d_t^* raises the value of $f(d_t,m,t_0)$ for $t_0<(1/h)$ that has a larger $z(t_0)+1$ while reducing the value of $f(d_t,m,t_0)$ for $t_0\geqslant(1/h)$ that has a relatively smaller $z(t_0)+1$. Overall, a larger d_t^* raises the expected market structure of consumption goods production, $E_t\left[z(t_0)\right]+1$. Hence, $\partial(E_t\left[z(t_0)\right]+1)/\partial d_t^*>0$.

Furthermore, in the derived formula for $\partial(E_t\left[z(t_0)\right]+1)/\partial d_t^*$,we find that when F rises the denominator of $\partial(E_t\left[z(t_0)+1\right]/\partial d_t^*$ increases and therefore, $\partial E_t\left[z(t_0)+1\right]/\partial d_t^*$ falls. Thus, the rate at which $E_t\left[z(t_0)\right]+1$ increases in d_t^* is decreasing in F. ■

A.6 Proposition 5: The expected market structure of consumption goods production, $E_t\left[z(t_0)\right]+1$,

(i) falls with more entry barriers, F, if the direct effect of F on discouraging imitation dominates;

(ii) rises with more entry barriers, F, if the indirect effect of F on encouraging product development investment – and therefore attracting more imitation – dominates.

Proof: Start with $d(E_t[z(t_0)]+1)/dF = [\partial(E_t[z(t_0)]+1)/\partial F]+[\partial(E_t[z(t_0)]+1)/\partial d_t^*][\partial d_t^*/\partial F]$. Now taking the derivative of $E_t[z(t_0)]$ with respect to F, we obtain:

$$\frac{\partial(E_t[z(t_0)]+1)}{\partial F} = -\frac{(E_t[z(t_0)]+1)}{F} < 0. \tag{a.17}$$

According to section A.5, $\partial(E_t[z(t_0)]+1)/\partial d_t^* > 0$, and according to section A.2, $\partial d_t^*/\partial F > 0$. Therefore, $d(E_t[z(t_0)]+1)/dF$ comprises of two opposite effects. The first term, $\partial(E_t[z(t_0)]+1)/\partial F < 0$, represents the direct effect of raising entry barriers on reducing imitation. The second term, $[\partial E_t[z(t_0)]+1)/\partial d_t^*]\ [\partial d_t^*/\partial F] > 0$, represents the indirect effect of higher product development effort on attracting more imitation. When the direct effect dominates, $d(E_t[z(t_0)]+1)/dF < 0$; when the indirect effect dominates, $d(E_t[z(t_0)]+1)/dF > 0$. ■

A.7 Proposition 6: The expected market structure of consumption goods production, $E_t[z(t_0)]+1$,

(i) rises with a longer patent length, when the imitation cost exceeds a certain level, F_2; falls with a longer patent length, when the imitation cost is sufficiently lower than F_2.

(ii) attains an interior maximum and has an inverted U-shape with respect to the legal patent length, L, when there is imitation.

Proof: Note $d(E_t[z(t_0)]+1)]+1)/dL = [\partial(E_t[z(t_0)]+1)/\partial L]+[\partial(E_t[z(t_0)]+1)/\partial d_t^*][\partial d_t^*/\partial L]$ and that $z(t_0)+1$ specified in equation (a.15) is an increasing function of L, and T, the upper bound of the support of the integral in equation (a.16), is also an increasing function of L. A larger L enables to take the increased expectation of (a.15) over a longer interval and raises $E_t[z(t_0)]+1$. Thus, $\partial(E_t[z(t_0)]+1)/\partial L > 0$. As shown in section A.5, $\partial(E_t[z(t_0)]+1)/\partial d_t^* > 0$. According to proposition 4, part (i), when $F > F_2$, $\partial d_t^*/\partial L > 0$. This indicates that $d(E_t[z(t_0)]+1)/dL > 0$. However, when F is sufficiently lower than F_2 such that the negative effect of the second term $([\partial(E_t[z(t_0)]+1)/\partial d_t^*]$

$[\partial d_t^*/\partial L] < 0$) outweighs the positive effect of the first term ($\partial(E_t [z(t_0)] + 1)/\partial L$), $d(E_t [z(t_0)] + 1)/dL < 0$. The intuition behind this result is that, in an extremely competitive industry, the innovator expects more imitators when patents are longer and has fewer incentives to develop the product.

Similar to A.4, $E_t [z(t_0)] + 1$ attains an interior maximum, and has an inverted U-shape with respect to the legal patent length, L. ■

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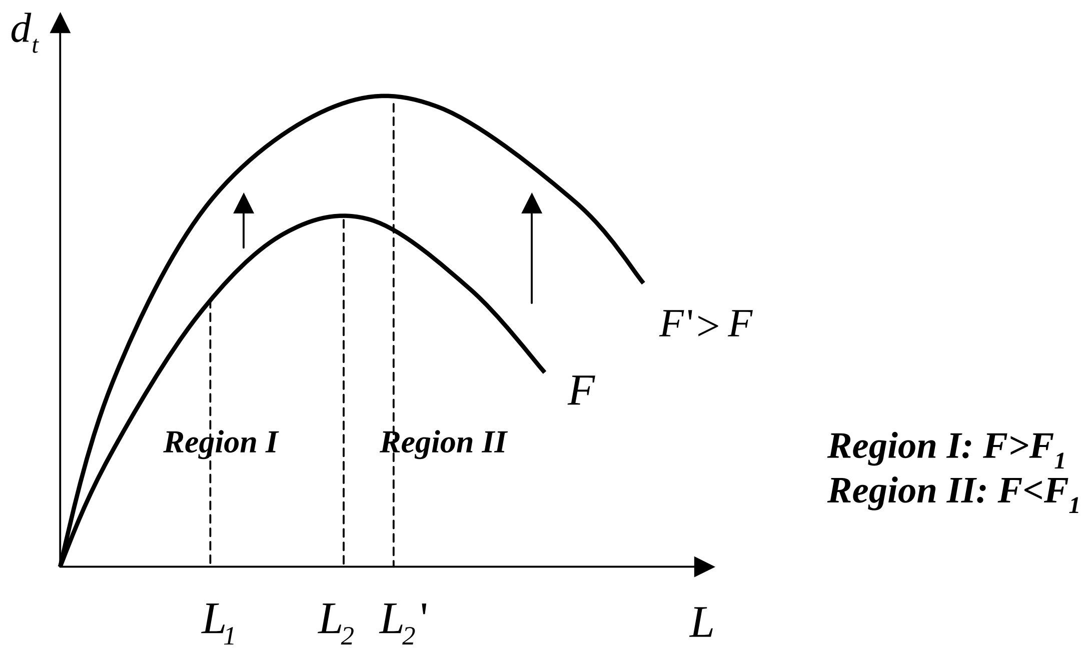

Figure 1: The relationship between
R&D and legal patent length

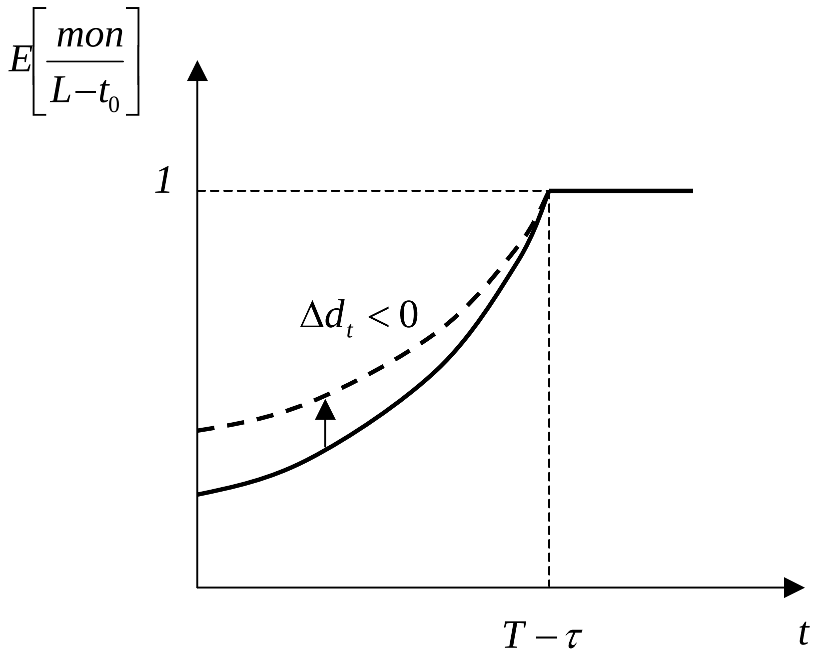

Figure 2.a: The effect of strategic delay on the effective patent protection over time

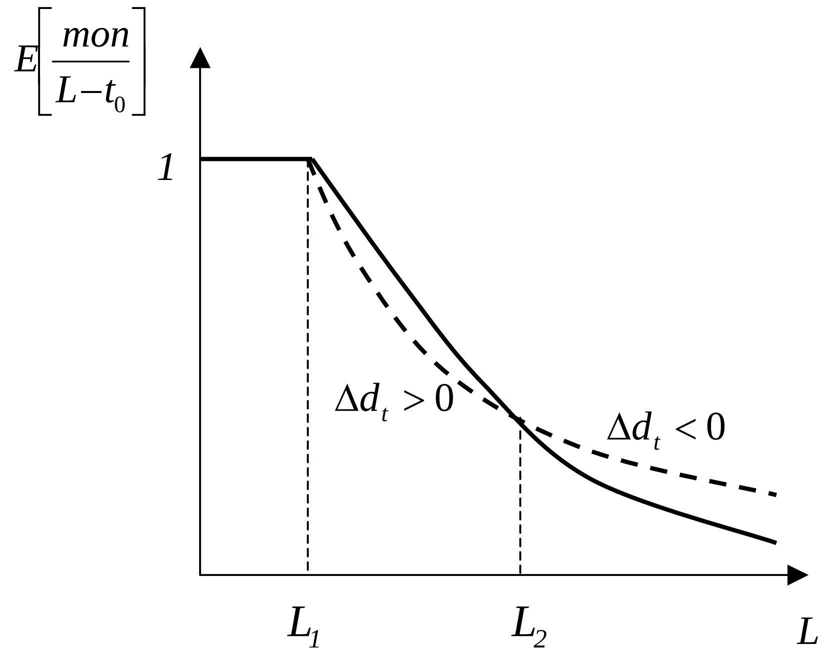

Figure 2.b: The effect of extending legal patent length on R&D and thus the effective patent protection

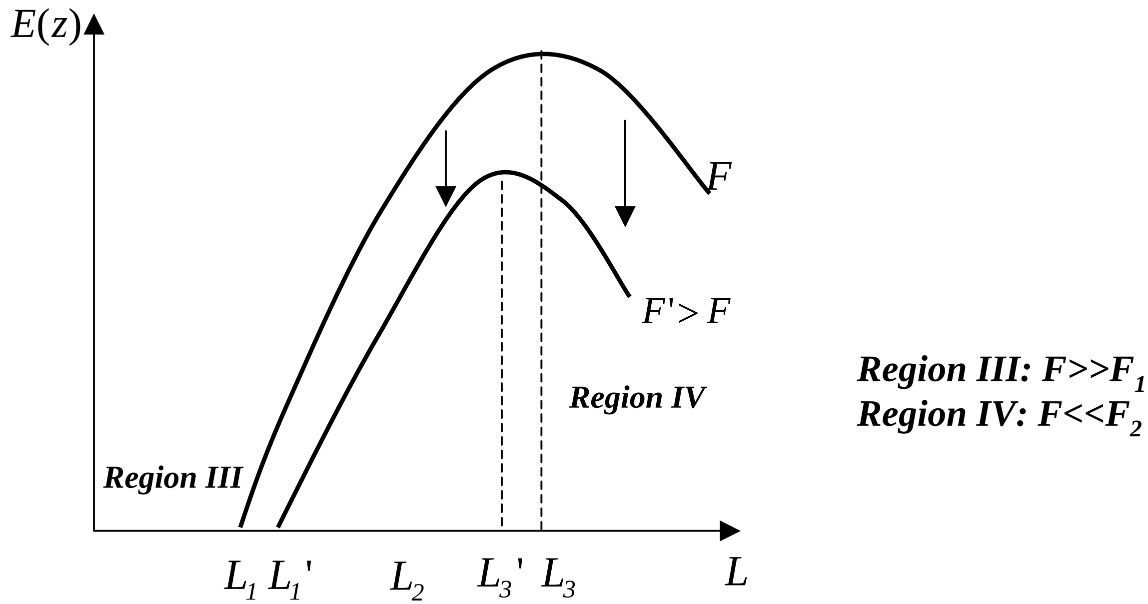

Figure 3: The relationship between
expected number of imitators and legal patent length

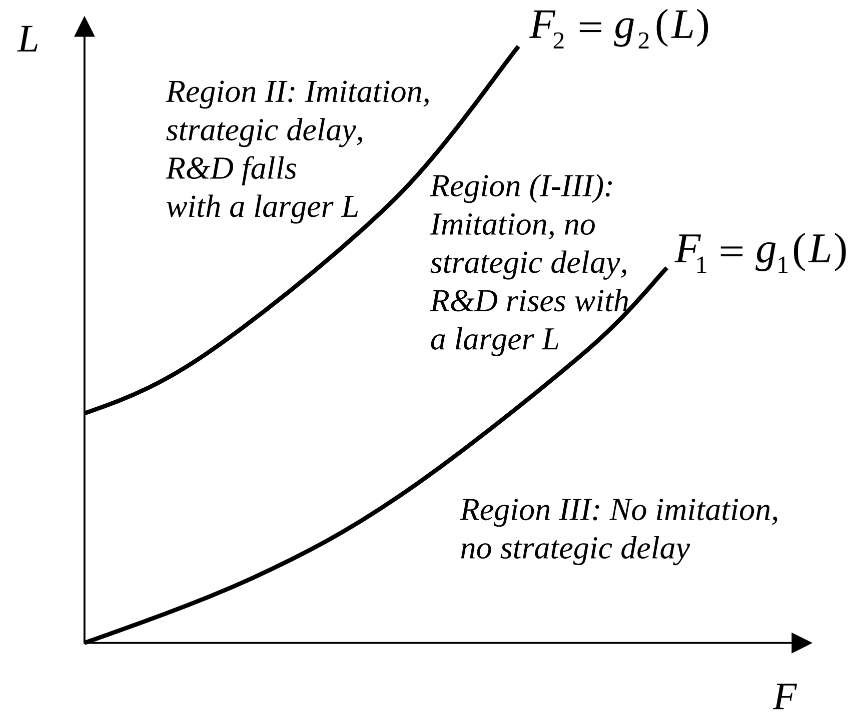

Figure 4: Imitation, strategic delay, R&D, and policy decisions