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ECONOMICS OF PATENTING A RESEARCH TOOL

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ABSTRACT

When a new technology consists of sequences of innovations that culminate in a final consumer product, the balance between successive innovators is one of the main concerns in the design of the patent system. While intertemporal aspects of incentive are critical in this environment of sequential innovations, time plays a minor role in existing literature on dynamic models. By focusing on the incentives of follow-on innovators who commercialize an initial invention, this study examines the dynamic implications of the patent instrument (e.g., patent life) via a positive analysis. It shows that a long patent life may encourage innovation incentives and increase social welfare, contrary to existing arguments that argue that long patent life always discourages the incentive for *subsequent* innovations. This study also examines the implications of finite patent system in different market structures.

Keywords: Patent life, Research tool, Licensing, Rent dissipation

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Bonwoo Koo [1]and Brian D. Wright[2]

1. INTRODUCTION

The current revolutions in biotechnology and information technology consist of sequences of innovations that culminate in a final consumer product. The concurrent revolution in intellectual property rights has resulted in patenting of elements of these innovation sequences. In biomedical science, for example, new research tools that play a critical role in subsequent innovations (e.g., cell lines, cloning tools, reagents, etc.) are being patented. One policy issue in this environment is how to provide an adequate incentive to develop research tools that can open up new lines of innovation. Another fundamental issue is how to promote dissemination of these tools for further follow-on developments by subsequent innovators.[3]

The balance of incentives between successive innovations has been the main concern in the recent dynamic literature on the design of the patent system. Some studies emphasize the positive effect of patenting on early innovation and support a strong patent system (e.g., Kitch 1977; Scotchmer 1996), while others express considerable concern over the potential negative effects of patents on subsequent innovations and propose weaker patent protection to reduce the problem of high transaction costs associated with licensing

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[3] Considerable concerns have been expressed on the limited access to the proprietary research tools in practice. See NIH (1998) for examples.

with multiple patent holders (see, for example, Merges and Nelson 1990; Heller and Eisenberg 1998).

Paradoxically, in most dynamic models time plays a minor role (Green and Scotchmer 1995; Chang 1995; O'Donoghue 1998). They typically focus on the size and division of innovation induced by varying degrees of patent breadth or scope, without much consideration on the relation between patent life and the date of introduction of subsequent innovations. Changes in patent life induce complex dynamic incentives: changes in patent life affect the period of overhang during which the follow-on innovator pays royalty fees to the previous patent holder, which in turn changes the date of introduction of subsequent innovations with different expected profit from the innovation.

This study investigates the implications of patenting when innovations form a dynamic sequence. Arguments for patent reform based on existing dynamic models may be premature if the implications of the *currently practiced* patent system itself are not properly appreciated in the context of a dynamic research sequence. This paper considers the sequence in which an initial invention is an input essential to a subsequent innovation that in turn lowers the cost of producing a consumer good. In a two-stage innovation model, this study analyzes the role that finite patent life can play in advancing (or delaying) the introduction of the second, follow-on innovation, by assuming an inelastic first invention.

The standard analysis on the justification of a finite patent life is based on the static Nordhaus (1969) model of an independent, stand-alone innovation that reduces the production cost of a consumer good. His derivation of an optimal *finite* patent life balances the gain from appropriability of the value of the innovation during the period of monopoly granted by the patent against the associated deadweight loss. The optimal life is sensitive to the parameters of the system including the size of innovation, the shape of the innovation production function, and particularly, the elasticity of demand for a consumer good. His model assumes no competition in the innovation process so that the lone innovator is guaranteed the receipt of a patent if she succeeds in achieving an innovation.

Two lines of research have been developed since the Nordhaus' seminal paper. One line of research focuses on the roles of patent instruments, along the line of the Nordhaus' original model of a monopolistic innovation process. Several studies (Gilbert and Shapiro 1990; Klemperer 1990; Gallini 1992) examined the optimal mix of patent breadth and length that provides a pre-determined level of reward to the patentee in a model of an independent innovation.[4] Subsequent studies of a two-stage model (Green and Scotchmer 1995; Chang 1995) and a multi-stage model (Cadot and Lipman 1995; Horowitz and Lai 1996) analyze the effect of patent breadth and life on the incentive for innovation and social welfare, without much regard to competitive innovation race. All of these models assume either a single firm pursuing an innovation or two firms competing for a patent where one firm merely plays a minor role as an imitative threat.

The other line of research from the Nordhaus model emphasizes the role of competitive patent race in the innovation process. By introducing competitive innovation race, Kamien and Schwartz (1974) derive an optimal patent life that is longer than that of Nordhaus and DeBrock (1985) and Denicolo (1999) derive a shorter life than Nordhaus'.

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[4] By treating the breadth of a patent as a decision variable, Gilbert and Shapiro argue that a narrow patent with infinite life is optimal, while Klemperer reaches a different result. Gallini shows that if imitators can invent around a patent, a short and broad patent is optimal.

This focus on competitive patent race subsequently extends to a two-stage model (Denicolo 2000) and a multi-stage model (O'Donoghue 1998). However, unrestricted R&D competition in the innovation race can result in the rent dissipation problem familiar in open-access resource models (Gordon 1954), and this affects social welfare and optimal patent system. Wright (1983;1984) demonstrates that the social loss associated with rent dissipation by competitive innovators can dominate the deadweight loss from monopoly awarded by a patent; more responsive research tends to imply that welfare-maximizing patents life is shorter.

In this paper, we focus on the case where the search for the second innovation is competitive and the timing of innovation is responsive to the rate of research. We first show that a long patent life might not hinder subsequent innovation when the R&D cost of the innovation is not sufficiently high (proposition 1). The possibility of licensing the first invention within its patent period makes this result possible. This result contrasts to existing studies on sequential innovations that argue that long patent life always discourages the incentive for *subsequent* innovations. However, this result does not necessarily imply that the optimal patent life is infinite. A finite patent life can encourage the search for subsequent innovations that would be blocked under infinite patent life, and proposition 2 shows that the optimal patent life is finite in all range of cost. Another important result of this study is that social welfare is in general not sensitive to patent life, and a finite patent system is self-selective due to firms' ability to adjust the timing of investment. Finally, we show that if competitive researchers dissipate their rents in racing for patents, endowing a potential innovator with monopoly power might be welfare improving when the R&D cost is very low.

The paper is organized as follows. Section 2 introduces a two-stage sequential innovation model amenable to analytical assessment, and discusses licensing equilibrium and efficient royalty for licensing a patent for use by a subsequent innovator. Assuming a first innovation has already been made, section 3 analyzes the incentive for the second innovation in a competitive innovation race and derives an optimal patent life that maximizes social welfare. The implications of a finite patent life and the importance of licensing arrangement are considered in this dynamic context. Section 4 considers the case where only a single firm can participate in the second innovation and compares the results with the competitive case of Section 3. Section 5 extends the model by relaxing some of assumptions, and concluding remarks follow in section 6.

2. A TWO-STAGE INNOVATION MODEL

2.1. ASSUMPTIONS

We adopt a highly stylized model with polar assumptions to focus on the issues that are of interest here. Consistent with other sequential models, we consider the case in which the second innovation ("application") builds upon a patented first invention.[5] The first invention is a "research tool" that does not impart any direct externality other than that it enables the search for the second innovation. To analyze the incentive for the second innovation in more detail, we assume the first invention is inelastically supplied. Initially, we assume that a successful first inventor cannot compete for the second innovation, so she must patent her invention to receive licensing revenue from a subsequent innovator. A

[5] We follow the classic differentiation between technological invention and commercial innovation, addressed by Schumpeter (1939). He defined an *innovation* as the commercial application or adoption of an

simple example is an independent researcher who receives a patent for a research tool (say, a screening method to identify novel compounds) but does not have the capacity to develop and commercialize its invention (say, into a new drug).

There is no fixed cost involved for the second innovation, so the market for the search for the second innovation is perfectly competitive with free entry, facilitated by common knowledge of the essential idea revealed by the patent on the first invention.[6] Following the tradition established by Loury (1979) and Lee and Wilde (1980), we assume each firm in the race chooses a Poisson hazard rate $\lambda \in R^+$ for a successful innovation and the marginal cost of λ is assumed to be constant at c.[7] To facilitate the analysis of this model, we also make a technical assumption that firms in the race commit investments for a period Δ in advance, where Δ may be arbitrarily small. An alternative assumption with equivalent implications is that there is a time lag Δ between a successful innovation outcome and the arrival of this news to research administrators including competitors, resulting in rent dissipation during Δ period. This is an intermediate case between Loury's assumption that a one-time initial investment generates a perpetual flow of research effort insensitive to the evolution of incentives, and Lee and Wildes' flow-cost model that assumes λ is an instantaneously variable input, ruling out competitive rent dissipation via research duplication.

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invention.

[6] If a fixed cost is required for the second innovation, a *finite* number of firms compete for the innovation and the innovation cannot be achieved instantaneously, as shown in lemma 1 in section 3 below. However, qualitative results remain the same with the inclusion of fixed cost.

[7] This assumption of constant marginal cost greatly simplifies the analysis, and also maximizes the possible waste engendered by patent race. The models by Green and Scotchmer (1995), Chang (1995), or Denicolo (1999) implicitly assume a constant cost of innovation.

The research tool does not directly produce any consumer good. Its flow value is v per period, accruing indirectly as a result of a reduction in the cost of a consumption good after achievement of the second innovation. To remove the static inefficiency of the patent monopoly addressed by Nordhaus as a reason for limitation of patent life, we assume a perfectly inelastic demand curve for the consumer good, with zero income effect. To focus on the dynamics of the innovation process itself, we assume the level of intertemporal demand is static, in contrast to Barzel (1968) who assumes a growing demand with increasing population.

Though, there are infinitely many ways of attempting to achieve the second innovation, we assume there are no substitute innovations. That is, the scope of a patent is assumed infinite in the sense that the patent cannot be "invented around" by producing a substitute during the protected period. Thus, an invention patented at time zero is fully protected till the end of the patent life, T, and a licensing agreement is required for commercialization of the second innovation before T. This assumption contrasts with some models with finite patent scope in which the second innovator effectively "invents around" the first and provides a substitute with lower production cost or other superior attributes, rendering the first patent obsolete (O'Donoghue 1998, Hopenhayn and Mitchell 2001). In their models, delay of the second innovation increases the first inventor's expected profit by extending her stream of revenue,[8] while in our model the delay reduces the expected profit because the expected stream of licensing revenue is shorter and starts later.

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[8] If no value is directly accrued from the first invention, as in the case of research tool, the expected profit of the first invention is zero in those studies.

Many types of *ex post* licensing arrangements are plausible for commercialization of the second innovation. One simple method is for the successful second innovator to pay an up-front fee to the first inventor for the right to use her patent until expiration. Another method, equivalent in our model, is to pay a share of the second innovator's revenue during the first patent period as a "running royalty." Potential second innovators can adjust the timing of their entry into the innovation race according to the level of the royalty. For purpose of exposition, our model assumes a running royalty, and the royalty rate is $\alpha \in [0, 1]$, the share of the revenue flow transferred from the second to the first inventor. Firms are assumed to be risk-neutral, and the discount rate is r.

2.2. LICENSING EQUILIBRIUM

The *ex ante*, exclusive licensing agreement addressed in the two-firm world of Green and Scotchmer is not feasible in an environment with atomistic competitive potential licensees. However, if only a single firm can participate in the second round innovation, *ex ante* agreement is a definite possibility. In this study, we focus on *ex post* licensing agreement in a competitive and monopolistic patent race, but the case of *ex ante* agreement in a monopolistic market structure is briefly considered in section 5 below.

Suppose that the second innovation is developed before the first patent expires. The first patent holder can block commercialization of the second innovation until her patent, received at date zero, expires at date T. The second patent holder can similarly block commercialization of his innovation (by the first patent holder), awarded at date t and expiring at $t + T$. Thus, the second innovation is vulnerable to the "double-holdup" problem (Merges and Nelson), preventing it from being utilized without a licensing agreement. But, if the gains from an agreement are greater than the status quo, both patent holders have strong incentive to arrange a licensing agreement. If a running royalty system is adopted, the surplus to be divided is the flow gross value v from the date of issue of the second patent (assumed identical to the date of discovery) until T, the date of expiration of the first patent. Assuming Nash bargaining with equal bargaining power, the solution is a 50-50 share of v until date T: that is, $\alpha = 0.5$.

There can be cases (e.g., when the innovation is expensive to develop) in which the first inventor would prefer to make a credible offer of a lower royalty rate (say, $\alpha < 0.5$) to render the second innovation more attractive to potential innovators. Under an infinite patent life, however, competitive innovators who anticipate a fifty percent share of revenue will not pursue the second innovation if the profit margin from the innovation is less than the present value of costs. An *ex ante* royalty rate below fifty percent, proclaimed unilaterally by the first inventor, is not credible *ex post*, because the first patent holder can renegotiate the royalty rate to fifty percent. The *ex post* royalty rate is thus 0.5, independent of the innovation cost. However, even if the royalty rate α stays at its equilibrium level of 0.5 and the expected cost is more than half the gross expected present value of the innovation, a second innovation with positive expected net social value can be induced, with a lag, by restriction of patent life to some value $T \in R^{+}$.

3. COMPETITIVE INNOVATION MARKET AND OPTIMAL PATENT LIFE

3.1. HAZARD RATE AND TIMING OF THE SECOND INNOVATION

Assuming the first patent is received at date zero, if the second innovation is made *t* periods after the first patent, the expected present value of the innovation, net of royalty, is

$$V(t) = (1-\alpha)\int_0^{T-t} ve^{-r\tau} d\tau + \int_{T-t}^{T} ve^{-r\tau} d\tau . \qquad (1)$$

During the overhang period till the first patent expires, the successful second innovator receives the flow revenue *v* net of the royalty fee to the first patent holder (the first term on the right hand side (RHS) of equation (1)). Beyond the overhang, the full revenue flow accrues to him until his own patent expires (the second term). The expected revenue of the second innovation depends on the period of overhang from the first patent, and the main decision by potential innovators is the timing of their entry into the race. The following lemma characterizes the timing and the intensity (or hazard rate) of the second innovation:

Lemma 1: Hazard rate of the second innovation under competition

Assume the expected net present value of the innovation to the second innovator V(t) exceeds the flow cost of search c. In the limit as the cost commitment period Δ approaches zero, if the second innovation has not yet been achieved, it is made instantaneously at date t and the expected profits are completely dissipated through competition.

Proof. Consider a decision at date t for $V(t) \geq c$. When n identical firms compete for an innovation, the industry-wide expected cost of the innovation, under the assumption of Δ-period commitment, is

$$C = e^{-r\Delta}\int_0^\infty \left(\int_0^{0\tau} cn\lambda e^{-ru}du\right) n\lambda e^{-n\lambda\tau}d\tau + \int_0^\Delta cn\lambda e^{-r\tau}d\tau .$$

The expected cost consists of the search cost incurred till a successful innovation and the extra cost incurred during an additional period Δ due to, for example, delayed news of a successful innovation.[9] The expected profit, evaluated at date t, is

$$\Pi(t) = \int_0^\infty V(t)n\lambda e^{-(r+n\lambda)\tau}d\tau - C = \frac{V(t)n\lambda}{r+n\lambda} - \left(\frac{cn\lambda e^{-r\Delta}}{r+n\lambda} + \frac{cn\lambda(1-e^{-r\Delta})}{r}\right).$$

With free entry, the zero profit condition yields the following industry hazard rate:

$$n\lambda = \frac{r\left[V(t)-c\right]}{c\left(1-e^{-r\Delta}\right)}.$$

For a positive rent ($V(t) - c > 0$), as Δ approaches zero we get

$$\lim_{\Delta\to 0} n\lambda = \frac{V(t)-c}{c\Delta} = \infty.$$

since $e^{-r\Delta} \cong \left(1-r\Delta\right)$ for a small Δ. Thus, as the commitment period Δ goes to zero, the industry hazard rate $n\lambda$ approaches infinity and the time before the innovation succeeds goes to zero almost surely. Q.E.D.

If the expected net present value $V(t)$ is lower than the constant cost c, firms will delay investment until the value exceeds the cost. Lemma 1 implies that at $t = t^*$ where $t^* = \inf\{V(t) \geq c\text{: } t\in R^+\}$, firms rush into the race and the innovation is, in the limit, made instantaneously.[10] Potential rents from the innovation are completely dissipated through

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[9] For expositional purpose, we assume the search cost starts to incur from date Δ and is discounted back to time zero (the first term on the RHS), and the extra cost is incurred during the period [0, Δ] (the second term).

[10] This derivation of an infinite hazard rate in our model of innovation is similar to the idea of an infinite exploration rate in a model of exploitation of exhaustible resource. Arrow and Chang (1982) claim without

competition. Though the fixed-cost model of Loury could explain rent dissipation, it does not allow for an instantaneous innovation; there is a fixed expected delay between resource commitment at the start of a race and the discovery of innovation, regardless of the intensity of innovative activity. On the other hand, Lee and Wilde's model of flow investment can explain instantaneous second innovation, but there is no rent dissipation in their model. Lemma 1 shows that our model with Δ-commitment can explain both rent dissipation and instantaneous innovation.

Given a first invention patented (and revealed) at $t = 0$, the timing of the second innovation is easily calculated. To simplify the exposition, we define the marginal cost of λ as a fraction of gross value of the innovation; i.e., $c \equiv kv/r$, where $k \in [0, 1]$ is the cost coefficient. The expected profit function of the second innovation is defined as

$$\pi(t) = V(t) - c = \frac{v}{r}\left[(1-\alpha) + \alpha e^{-r(T-t)} - e^{-rT} - k\right]. \tag{2}$$

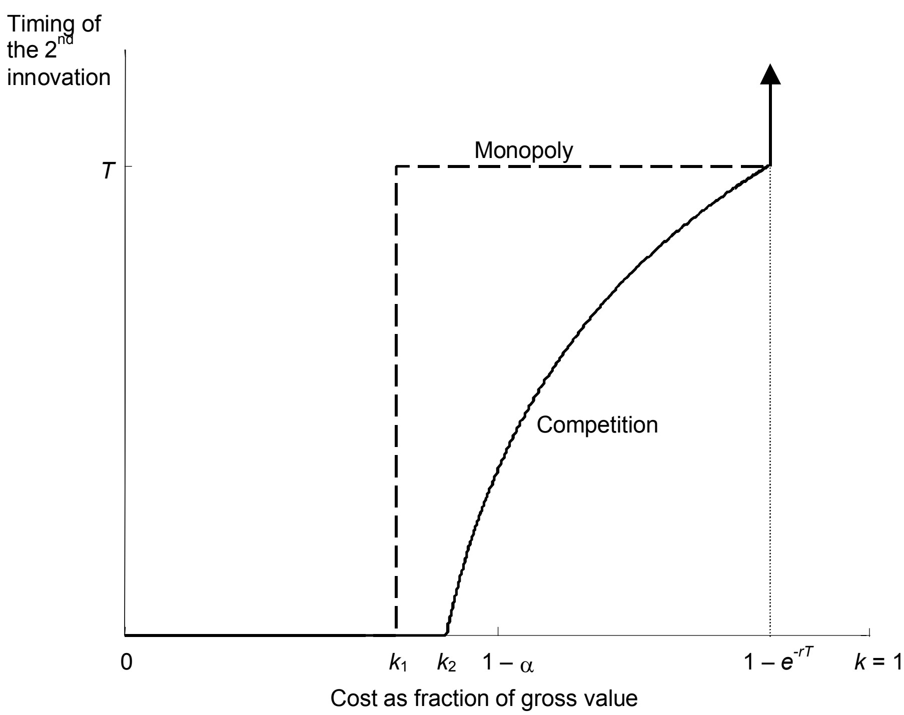
If the marginal cost is lower than the expected value when a firm makes an innovation immediately after the first patent ($c \leq V(0)$ or $k \leq (1-\alpha)(1-e^{-rT})$), then the second innovation follows immediately at date $t = 0$. On the other hand, if the marginal cost of search exceeds the value of the second innovation when it is introduced after the expiration of the first patent ($c > V(T)$ or $k > 1-e^{-rT}$), the second innovation will never be made. For an intermediate range of marginal cost ($(1-\alpha)(1-e^{-rT}) < k \leq (1-e^{-rT})$), the second innovation is made within the first patent life at time t^* when the expected profit is zero. In the limit as Δ goes to zero, the timing of the second innovation is summarized as:

proof that the resource exploration rate can, in the limit, be infinite when the exploration costs are linear.

$$t^* = \begin{cases} 0 & \text{if } 0 \le k \le k_2 \equiv (1-\alpha)(1-e^{-rT}) \\ -\frac{1}{r}\ln\left(\frac{\alpha e^{-rT}}{e^{-rT}-(1-\alpha)+k}\right) & \text{if } k_2 < k \le k_3 \equiv (1-e^{-rT}) \\ \infty & \text{if } k_3 < k \le 1 \end{cases} \quad . \qquad (3)$$

Figure 1 shows the timing of the second innovation under different levels of cost, when patent life is fixed at *T*. It shows that the timing under a competitive innovation race (the solid line) is a non-decreasing function of the marginal cost (or the cost coefficient *k*). Proposition 1 examines how the timing is affected by a change in patent life.

Figure 1--Timing of the second innovation



Proposition 1: Patent life and timing of the second innovation

Given a first invention patented at t = *0*, an increase in patent life from T advances the timing of the second innovation $t^*(T)$ if the marginal cost of search for the second innovation is in an intermediate range, $(1-\alpha)(1-e^{-rT}) < k \le (1-\alpha)$.

Proof. Total differentiation of equation (2) for $t = t^*$, where $0 < t^* < T$, yields

$$\frac{dt^*}{dT} = -\frac{e^{-rT}}{\alpha e^{-r(T-t^*)}} + 1 .$$

A longer patent life increases the expected revenue of the second innovation by lengthening the stream of revenue from the innovation, resulting in earlier innovation (the first term on the RHS). On the other hand, the net revenue decreases with a longer patent life because the period of royalty payment to the first patent holder is lengthened (the second term). When the cost of the innovation is in the intermediate range $(1-\alpha)(1-e^{-rT}) < k \leq (1-\alpha)$, the first effect dominates the second and a longer patent life induces earlier second innovation. For a high cost ($1-\alpha < k < 1-e^{-rT}$), the second effect dominates the first and a longer patent life delays the second innovation. When the cost is sufficiently low ($k < (1-\alpha)(1-e^{-rT})$), the second innovation is instantaneous and change in patent life does not affect the timing of innovation. Thus, the effect of patent life on the timing of the second innovation is summarized as:

$$\frac{dt^*}{dT}\begin{cases} = 0 & if \;\; 0 \leq k \leq (1-\alpha)(1-e^{-rT}) \\ < 0 & if \;\; (1-\alpha)(1-e^{-rT}) < k \leq (1-\alpha) \\ > 0 & if \;\; (1-\alpha) < k \leq (1-e^{-rT}) \end{cases} . \qquad \text{Q.E.D.}$$

Existing studies on sequential innovations argue that long patent life always discourages incentive for *subsequent* innovations, but proposition 1 demonstrates the possibility of the opposite case. If the cost of the second innovation is not large, the size of a longer stream of revenue due to a longer patent life dominates the size of a longer payment of royalty fee to the first patent holder and the second innovation is advanced.

The possibility of licensing the first invention within its patent period makes this result possible.[11]

If the cost of innovation is high ($k > 1 - \alpha$) and the patent life is set as infinite, the expected value is less than the cost and the second innovation will not be made. Though the first patent holder has a strong incentive to induce the second innovation by lowering the royalty rate, he cannot credibly guarantee a low royalty rate due to the assumed absence of commitment capacity against *ex post* renegotiation once the R&D investment for the second innovation is sunk. Instead, if government sets a finite patent life, any second innovation that offers a positive profit stream at that patent life, net of marginal cost, will be pursued by competitive innovators at some time before (or at) the end of the life of the first patent. A finite patent life T provides a credible commitment to potential second innovators that the first inventor's royalty revenue (or share of the value of the second innovation) will definitely decline with time, to zero at $t = T$. This indicates that society may be better off with a finite patent life since it can induce, otherwise unavailable, second innovation.

3.2. SOCIAL WELFARE AND OPTIMAL PATENT LIFE

The social welfare under a competitive innovation race is expressed as

$$S_c(t^*) = \frac{\alpha v}{r}\left(e^{-rt^*} - e^{-rT}\right) + \frac{v}{r} e^{-r(t^*+T)}. \tag{4}$$

The first term on the RHS of equation (4) is the rent transferred to the first patent holder from the start of the second innovation t^* until the end of the first patent T. The

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[11] However, this result does not necessarily imply that the patent life should be infinite within this range of

second term is the consumers' surplus accrued after the expiration of the second patent, at $t^* + T$. The rent to the successful second innovator, net of royalty fee to the first patent holder, is completely dissipated through free entry. The level of social welfare for different ranges of cost is summarized as:

$$S_c = \begin{cases} \dfrac{v\left[\alpha + (1-\alpha)e^{-rT}\right]}{r} & \text{if } 0 \le k \le k_2 \equiv (1-\alpha)\left(1-e^{-rT}\right) \\ \dfrac{\alpha v e^{-rT}(1-k)}{r\left[e^{-rT} + k - (1-\alpha)\right]} & \text{if } k_2 < k \le k_3 \equiv \left(1-e^{-rT}\right) \\ 0 & \text{if } k_3 < k \le 1 \end{cases} \quad . \quad (5)$$

The solid line in Figure 2, $S_c(T)$, indicates the level of social welfare under competition when patent life is finite at T.[12] For $0 < k \le k_2$, as the cost decreases from k_2 the potential rent from the innovation increases but this rent is completely dissipated with free entry. Only a share of the rent transferred to the first patent holder as royalty fee and consumer surplus accrued after the expiration of the second innovation constitute as social welfare. Since the timing of the second innovation is the same (i.e., $t^* = 0$) within this range of cost, the sizes of the royalty payment and consumer surplus are constant and so is social welfare. As the cost level increases above k_2, social welfare decreases due to not only the higher current cost of innovation but also the delay in the second innovation. Social welfare drops to zero when the cost exceeds $1 - e^{-rT} (\equiv k_3)$.

The dashed line at the bottom of figure 2, $S_0(T)$, shows the level of social welfare when there is no possibility of licensing, as assumed by Horowitz and Lai. The race for the

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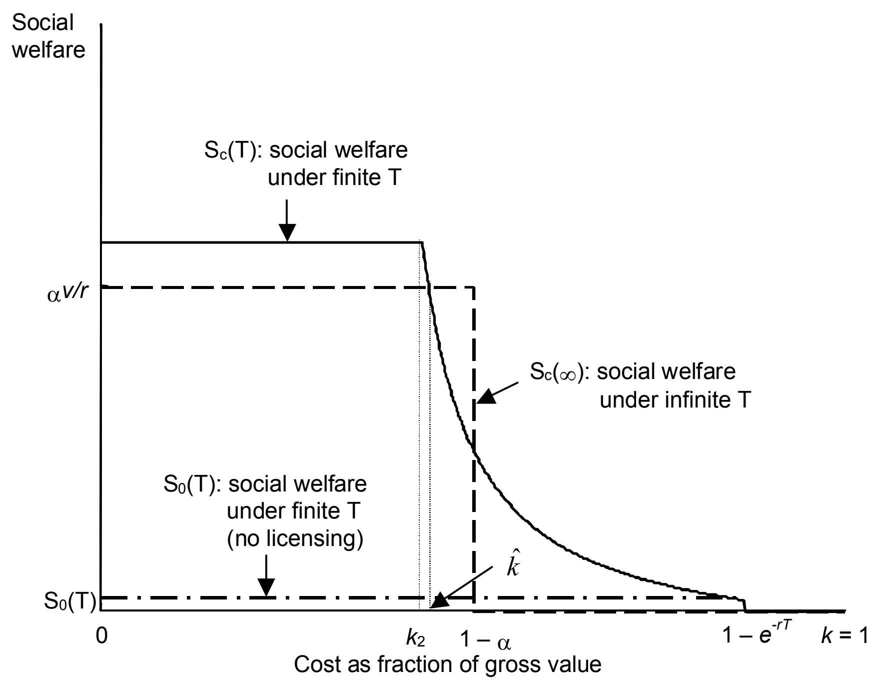
cost. See proposition 2 below.

[12] The parameters used in the figures are as follows: $v = 1$, $r = 0.1$, $T = 20$, $\alpha = 0.5$.

second innovation starts only after the first patent expires, and without any royalty payment to the first patent holder all rent from the innovation is completely dissipated through competition. Consumer surplus after the expiration of the second patent remains the only term of social welfare in this case. However, if a licensing agreement is allowed before the first patent expires, the second innovation is advanced and social welfare increases from $S_0(T)$ to $S_c(T)$, for all range of cost. A mechanism that facilitates a licensing agreement can be welfare improving when the innovation race is competitive.

Figure 2--Social welfare under competition



If patent life is infinite, the second innovation is either immediately made after the first patent for $k \leq 1 - \alpha$ or never made for $k > 1 - \alpha$ (the dotted line $S_c(\infty)$ in figure 2). With zero consumer surplus under an infinite patent life and complete rent dissipation due to free entry, social welfare consists only of the royalty fee transferred to the first patent holder. Society is better off under an infinite patent life if the cost of the second innovation is in a narrow range of $\hat{k} < k < (1 - \alpha)$. For most other range (i.e., $k < \hat{k}$ and $(1 - \alpha) < k \leq k_3$), however, finite patent life is socially desirable since there is less rent dissipation (for a low cost) or the second innovation is induced (for a high cost).

Proposition 2: Optimal patent life under perfect competition

When the innovation race is competitive, there exists a finite patent life T* that attains the maximum social welfare for all values of the cost, $0 \leq k < 1$.

Proof. Total differentiation of equation (5) with respect to patent life yields:

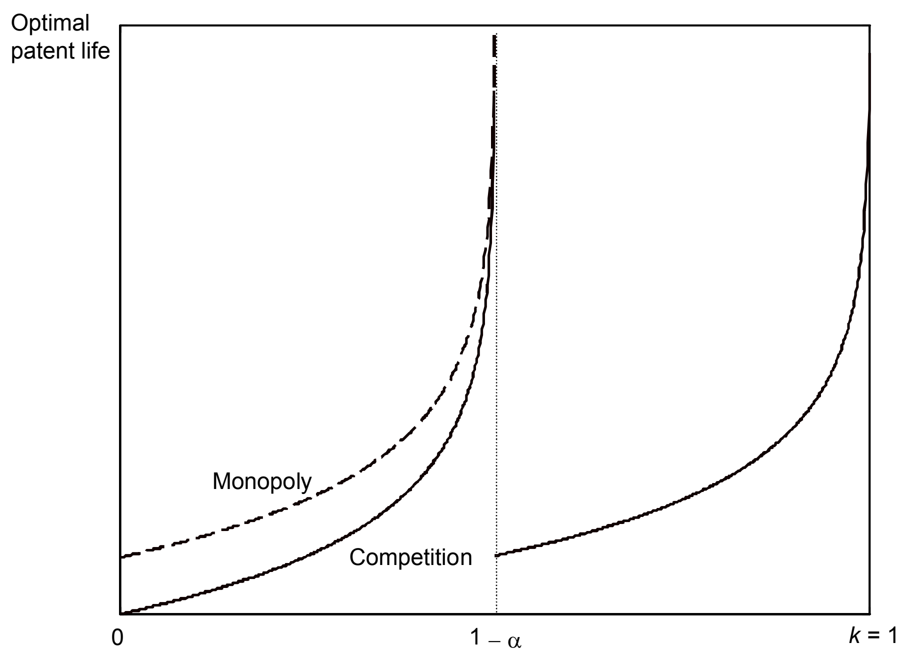
$$\frac{\partial S_c}{\partial T} = \begin{cases} -v(1-\alpha)e^{-rT} & \text{if } 0 \leq k \leq k_2 \\ \dfrac{\alpha v e^{-rT}(1-k)}{\left[e^{-rT} - (1-\alpha) + k\right]^2}\left[(1-\alpha) - k\right] & \text{if } k_2 < k \leq k_3 \\ 0 & \text{if } k_3 < k \leq 1 \end{cases}.$$

For a low cost ($0 \leq k \leq k_2$), the sign of $\partial S_c/\partial T$ is negative, implying that a shorter patent life increases social welfare. The minimum patent life that induces the second innovation within this range of cost is derived from the upper bound, k_2: i.e., $T^* = -\log\left[(1-\alpha-k)/(1-\alpha)\right]/r$. When the cost is in an intermediate range ($k_2 < k \leq k_3$), the sign of $\partial S_c/\partial T$ depends on the level of k: i.e., positive for $k_2 < k < (1-\alpha)$ and negative for $(1-\alpha) < k \leq k_3$. Thus, the optimal patent life is derived from the lower bound k_2 for $k_2 < k < (1-\alpha)$ and from the upper bound k_3 for $(1-\alpha) < k \leq k_3$. For a very high cost ($k_3 < k < 1$), no second innovation is made and social welfare is zero regardless of patent life.[13] The patent life that maximizes social welfare is summarized as:

[13] Though patent life doesn't affect social welfare within this range of cost, the minimum patent life derived from the lower bound k_3 is included here for expositional purpose.

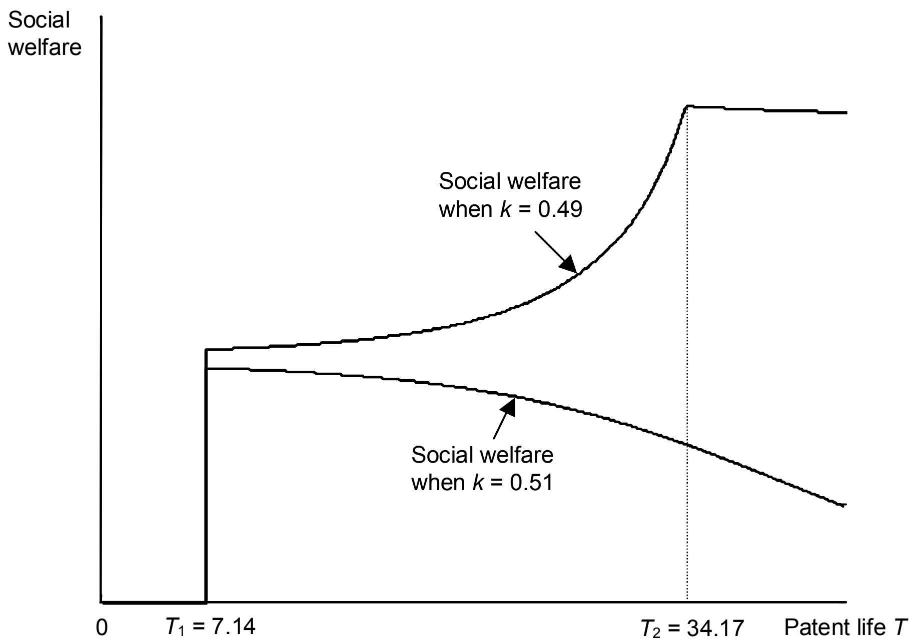
$$T^* = \begin{cases} -\dfrac{1}{r}\log\left(\dfrac{1-\alpha-k}{1-\alpha}\right) & \text{if } 0 \le k \le (1-\alpha) \\ -\dfrac{1}{r}\log(1-k) & \text{if } (1-\alpha) < k \le 1 \end{cases}. \qquad (6) \qquad \text{Q.E.D.}$$

Figure 3--The effect of research cost on optimal patent life



Proposition 2 illustrates that *finite* patent life is socially optimal for most range of cost, in a sequential context. When the cost of innovation is low ($0 < k \le (1-\alpha)(1-e^{-rT})$), a finite short patent life reduces the common pool problem associated with excessive competition, without delaying the innovation. Similarly, for a high cost ($k > 1 - \alpha$), a finite patent life provides a credible commitment that the first patent holder will not exploit the innovation and thus induces the second innovation. When the cost is in an intermediate level ($(1-\alpha)(1-e^{-rT}) < k \le 1-\alpha$), proposition 1 shows that the second innovation is advanced with a longer patent life. However, as patent life increases, the marginal loss from delayed incidence of consumer surplus dominates the marginal gain from earlier second innovation, and there exists a finite patent life that maximizes social welfare within this range of cost. Figure 3 illustrates that the optimal life correspondence admits a finite optimal patent life for all range of k (except when $k = 1$).[14]

Figure 4--Sensitivity of social welfare under alternative patent lives



While the optimal patent life is highly variable for an intermediate range of cost in figure 3, it turns out the actual level of social welfare is not so sensitive to the choice of patent life. Figure 4 shows the level of social welfare as a function of patent life under different values of cost k, similar to the graph by Nordhaus (figure 5.6, p. 83).[15] When k = 0.49, the patent life that maximizes social welfare is T_2 = 39.13 years. However, at least half the possible social welfare from a sub-optimally chosen patent life is attained as long

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[14] When $k = 1 - \alpha$, social welfare is constant, regardless of the level of patent life. The minimum patent life that induces the second innovation, however, is finite as indicated in figure 3.

as the patent life is longer than T_1 (= 7.14 years). Similarly, for $k = 0.51$, the optimal patent life is $T_1 = 7.14$ years and other patent lives that are longer than this level have only a minor impact on the social welfare. This implies that the current system of a finite patent life is self-selective in that firms can adjust their timing of investment to mitigate the research distortion cause by a patent.

4. MONOPOLISTIC INNOVATION MARKET AND OPTIMAL PATENT LIFE

4.1. TIMING OF THE SECOND INNOVATION

Now, consider a situation where only a single firm (possibly the first inventor) can pursue the second innovation. For example, if a single firm has an asset that is a "crucial complement" to the first invention, only that firm can develop the follow-on innovation as a monopolist. The first patent holder is likely to identify the single potential second innovator before an investment is made, and *ex ante* licensing agreement is plausible. In this section, however, we focus on the case of *ex post* agreement to compare it with the case of competition in the previous section. The *ex ante* agreement will be considered in section 5.

Lemma 2: Hazard rate of the second innovation under monopoly

Assuming a positive rent and a constant cost of innovation, as the commitment period Δ approaches zero, the second innovation occurs instantaneously when the monopolist makes an investment.

Proof. The monopolist's expected profit under the assumption of Δ-period commitment, evaluated at date t, is

[15] In figure 4, we consider the cost of innovation as $k = (1 - \alpha) \pm \varepsilon$, where $\alpha = 0.5$ and $\varepsilon = 0.01$.

$$\pi(t) = \frac{V(t)\lambda}{r+\lambda} - \frac{c\lambda e^{-r\Delta}}{r+\lambda} - \frac{c\lambda(1-e^{-r\Delta})}{r}.$$

The first order condition to maximize the expected profit yields

$$\lambda = \sqrt{\frac{r\left(V(t)-c\right)}{c\Delta} + r^2} - r$$

since $e^{-r\Delta} \cong \left(1 - r\Delta\right)$ for a small Δ. Assuming $V(t) \geq c$, as Δ approaches zero the monopolist's hazard rate λ approaches infinity: that is, $\lim_{\Delta\to 0} \lambda = \infty$. Q.E.D.

Like the case of competition in lemma 1, lemma 2 implies that the innovation is made instantaneously once the monopolist starts to make an investment. The difference is, however, that the hazard rate is of smaller order under monopoly (though it approaches infinity), so the monopolist can capture positive rent.

Without any threat of entry or competition, the monopolist can delay his investment even when the expected value exceeds the cost. The monopolist's expected profit is

$$\pi(t) = \frac{v}{r}\left[(1-\alpha-k)e^{-rt} + \alpha e^{-rT} - e^{-r(T+t)}\right]. \tag{7}$$

The timing of investment to maximize the monopolist's expected profit is derived from the first order condition of equation (7).

$$\frac{\partial\pi}{\partial t} = ve^{-rt}\left[-(1-\alpha-k) + e^{-rT}\right] = 0$$

The first order condition shows the timing of investment is independent of the period of overhang from the first patent. That is, the monopolist decides to invest either at time $t = 0$ when the sign of $\partial\pi/\partial t$ is negative or at time $t = T$ when it is positive. The timing of the second innovation under monopoly is summarized as

$$t^m = \begin{cases} 0 & if\ \ 0 \le k \le k_1 \equiv (1-\alpha) - e^{-rT} \\ T & if\ \ k_1 < k \le k_3 \equiv (1 - e^{-rT}) \\ \infty & if\ \ k_3 < k \le 1 \end{cases} . \tag{8}$$

Figure 1 shows that the second innovation is (weakly) delayed under monopoly (the dotted line) compared to the competition (the solid line), and the delay is longer when the cost is in an intermediate range (say, $k_1 < k < k_2$). Within this range of cost, the second innovation is made immediately after the first patent under competition because the expected rent is positive and firms rush into the innovation race. Under monopoly, however, the second innovation is delayed until the first patent is expired because delayed entry maximizes the monopolist's profit. This implies that *ex ante* agreement is not only likely to be more feasible if there is only one firm that can innovate in the second round; it is more important for the first inventor's profit. The second innovator has a bargaining advantage in the negotiation of *ex ante* agreement when earlier introduction of this innovation is jointly profitable. As the cost increases from k_2, the second innovation is delayed even under competition due to higher cost of innovation, and the difference in timing due to structure of the innovation market gradually vanishes.

4.2. THE OPTIMAL PATENT LIFE

The social welfare under monopoly consists of the monopolist's rent (equation (7)) as well as the consumers' surplus and royalty fee transferred to the first patent holder (equation (4)).

$$S_m(t^m) = \pi(t^m) + S_c(t^m) = \frac{v(1-k)e^{-rt^m}}{r}$$

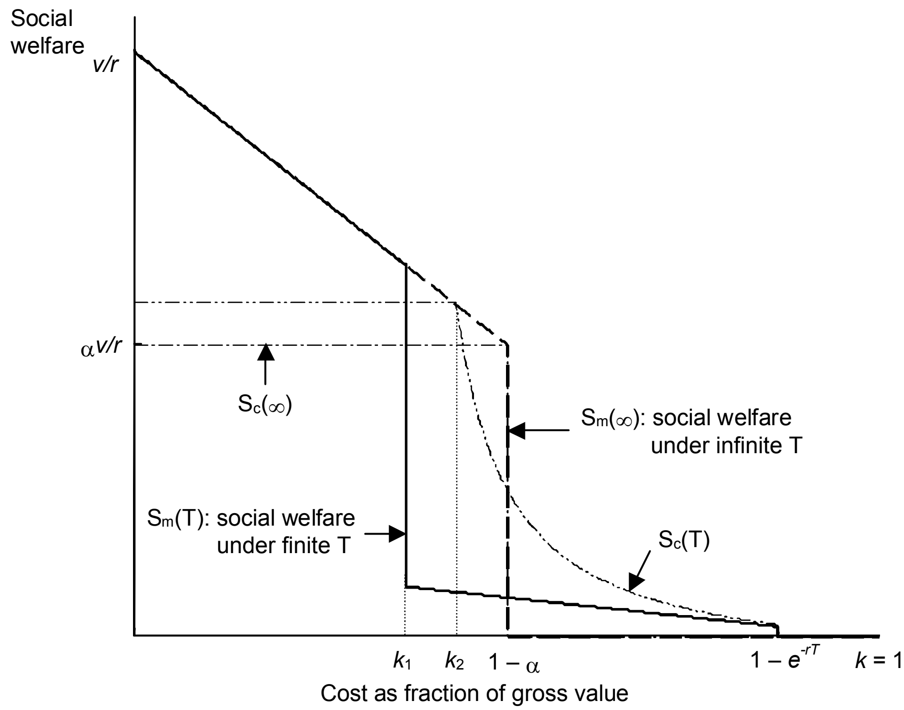
The social welfare under different cost levels is summarized as

$$S_m = \begin{cases} \dfrac{v(1-k)}{r} & \text{if } 0 \le k \le k_1 \equiv (1-\alpha) - e^{-rT} \\ \dfrac{v(1-k)e^{-rT}}{r} & \text{if } k_1 < k \le k_3 \equiv (1-e^{-rT}) \\ 0 & \text{if } k_3 < k \le 1 \end{cases} \quad . \tag{9}$$

The solid line in Figure 5, $S_m(T)$, indicates the social welfare under second round monopoly and *ex post* licensing, for a given finite patent life. As the cost increases from zero, social welfare decreases due to reduced monopoly rent associated with higher R&D cost. When the cost reaches k_1, social welfare drops down because the second innovation is suddenly delayed from $t = 0$ to $t = T$. With this delay, the royalty fee to first patent holder becomes zero and the present value of the monopolist's rent is substantially reduced, resulting in lower social welfare. Social welfare again drops to zero when the R&D cost is too high to induce any innovation ($k > k_3$).

Compared to the welfare under competition (the dotted line $S_c(T)$ in figure 5), social welfare under monopoly is smaller when the cost of innovation is high ($k_2 < k < k_3$) due to delayed second innovation. However, for a relatively low cost of innovation ($k < k_2$), monopoly can be better than competition. With immediate second innovation under both market structures but no rent dissipation under monopoly, social welfare under monopoly is larger by the size of the monopolist's rent. Monopoly prevents the common pool problem of competitive innovation race without significantly delaying the innovation. This implies that if the first inventor can efficiently make the second innovation (i.e., with a low cost), it can be welfare-improving to grant exclusive monopoly rights to the first inventor even if there are many competitors for the second innovation, as proposed by Kitch's (1977) "prospect theory."

Figure 5--Social welfare under monopoly



Under monopoly, figure 5 shows that infinite patent life can bring a larger social welfare than finite patent life ($S_m(\infty)$ vs. $S_m(T)$) for an intermediate range of cost ($k_1 < k < 1 - \alpha$).[16] Within this range of cost, a longer patent life advances the second innovation from T to zero and social welfare increases. However, as the patent life goes to infinity, the lower bound of the cost, k_1, approaches $1 - \alpha$, and the range where infinite patent life dominates vanishes. This implies that the optimal patent life under monopoly is finite, as proposition 3 shows.

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[16] Given an infinite patent life (and assuming all potential innovators have similar innovative capacity), the social welfare under monopoly ($S_m(\infty)$) is never less than the welfare under competition ($S_c(\infty)$) because rent dissipation is avoided under monopoly for $k < (1 - \alpha)$.

Proposition 3: Optimal patent life under monopoly

Under a monopolistic innovation market, there exists a finite patent life T^m that maximizes social welfare.

Proof. Total differentiation of equation (9) with respect to patent life yields:

$$\frac{\partial S_m}{\partial T} = \begin{cases} 0 & if\ \ 0 \le k \le k_1 \\ -v(1-k)e^{-rT} & if\ \ k_1 < k \le k_3 \\ 0 & if\ \ k_3 < k \le 1 \end{cases}.$$

For a low cost ($0 \le k \le k_1$), the second innovation is immediately made after the first patent and the society is indifferent to the length of patent life. The minimum patent life that induces the second innovation is derived from the upper bound k_1: i.e., $T_m = -\log(1-\alpha-k)/r$. For an intermediate range of cost ($k_1 < k \le k_3$), the sign of $\partial S_m/\partial T$ is negative. However, the lower bound $k_1 \equiv (1-\alpha) - e^{-rT}$ cannot exceed $(1-\alpha)$ and the upper bound $k_3 \equiv 1 - e^{-rT}$ cannot be less than $(1-\alpha)$ as long as the innovation is made. Thus, the optimal patent life is derived from the lower bound for $k_1 < k \le 1-\alpha$ and from the upper bound k_3 for $1-\alpha < k \le k_3$ (i.e., $T_m = -\log(1-k)/r$). For a very high cost ($k_3 < k < 1$), social welfare is independent of patent life and the lower bound k_3 is used to derive the minimum patent life. The optimal patent life that maximizes social welfare is summarized as

$$T_m = \begin{cases} -\dfrac{1}{r}\log(1-\alpha-k) & if\ \ 0 \le k \le (1-\alpha) \\ -\dfrac{1}{r}\log(1-k) & if\ \ (1-\alpha) < k \le 1 \end{cases}. \qquad (10) \qquad \text{Q.E.D.}$$

The dashed line in figure 3 illustrates that the optimal patent life is in general longer under monopoly than under competition. In particular, for $k < (1 - \alpha)$, the monopolist can capture all the rent and a longer patent life can be optimal. Under competition, on the other hand, the innovation race completely dissipates the increased rent (net of royalty) caused by an increase in patent life, without significantly advancing the second innovation.

5. EXTENSIONS

5.1. *EX ANTE* VS. *EX POST* LICENSING AGREEMENT

When the second innovation race is monopolistic, the single potential second innovator can be easily identified before an investment is made, and an *ex ante* licensing agreement is a possible scenario. With an *ex ante* agreement, the first inventor shares part of the R&D cost of the second innovation if she wants to induce it within her patent life. The expected profit from the second innovation, if the first inventor pays α percent of the R&D cost, is[17]

$$\pi(t) = \frac{v}{r}\left[(1-\alpha)(1-k)e^{-rt} + \alpha(1-k)e^{-rT} - e^{-r(T+t)}\right].$$

Using the same argument as before, the timing of the second innovation under an *ex ante* licensing agreement in a monopolistic market structure is summarized as:

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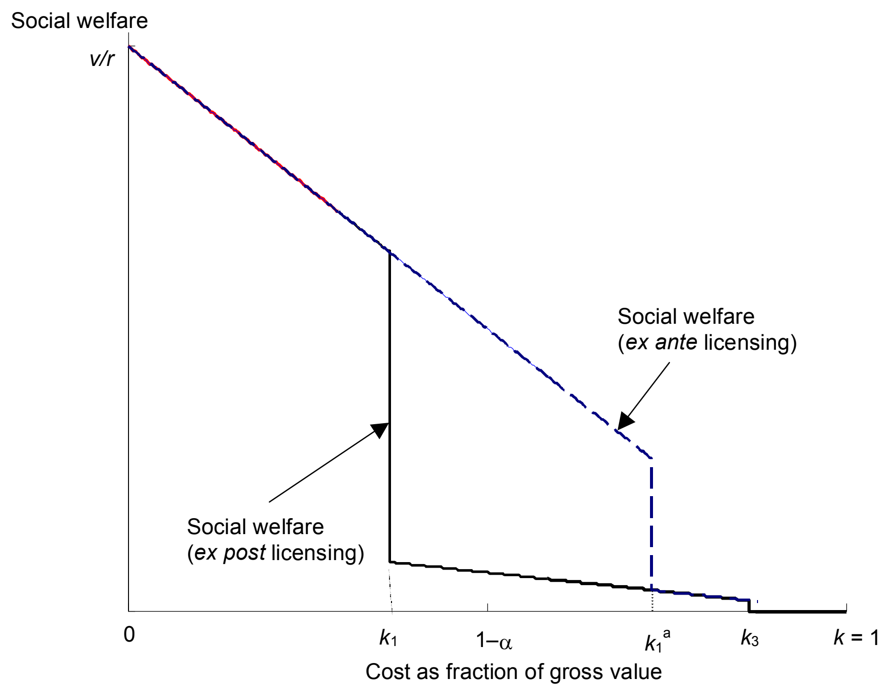
[17] The expected revenue from the second innovation at date $t < T$, is $v\left[(1-\alpha)e^{-rt} + \alpha e^{-rt} - e^{-r(t+T)}\right]$. The expected R&D cost borne by the second innovator is the total R&D cost (kve^{-rt}/r) minus the R&D cost shared by the first inventor during the overhang period ($\alpha kv\left[e^{-rt} - e^{-rT}\right]/r$).

$$t^m = \begin{cases} 0 & \text{if } 0 \le k \le k_1^a \equiv (1-\alpha-e^{-rT})/(1-\alpha) \\ T & \text{if } k_1^a < k \le k_3 \equiv 1-e^{-rT} \\ \infty & \text{if } k_3 < k \le 1 \end{cases} .$$

By sharing the R&D cost with the first inventor, the second innovator receives a larger profit and the innovation is advanced accordingly. The timing of the second innovation under *ex ante* agreement is similar to that of *ex post* agreement, except that the range of the cost with an immediate innovation is broader under *ex ante* agreement. The assumption of "no delay between two innovations" by Green and Scotchmer can be justified when the cost of the second innovation is not high ($0 < k < k_1^a$) in our model.

Figure 6 compares the social welfare under *ex ante* agreement with the welfare under *ex post* agreement. As the cost increases from zero, social welfare under *ex post* agreement (the solid line) suddenly drops at $k = k_1$ due to delay of the second innovation till the first patent expires. However, if an *ex ante* agreement is allowed, delay of the second innovation does not occur until the R&D cost reaches k_1^a due to the sharing of the R&D cost with the first inventor. For $k_1 < k < k_1^a$, the second innovation is advanced to $t =$ 0 from $t = T$ with an *ex ante* agreement. For a very cheap innovation ($0 < k < k_1$) or a very expensive one ($k > k_1^a$), however, the benefit of cost sharing from an *ex ante* agreement disappears since the date of introduction of the second innovation is independent of the timing of a licensing agreement.

Figure 6--Social welfare under monopoly: *ex ante* vs. *ex post* agreements



5.2. IMPLICATION OF THE 18-MONTH PERIOD PUBLICATION

In most countries, patent applications are made public 18 months after the application is filed, and the U.S. patent system began to follow this rule beginning in 2000.[18] Before this change, information of a patent application in the U.S. was not published until the patent was granted. One of the reasons for this new rule was to expedite the diffusion of knowledge revealed in patent applications. With an average lag of 28 months between patent application and grant in the U.S. (Johnson and Popp 2000), the rule can speed up the diffusion of patent information through early publication. However, it is also argued that this new rule may lead to fewer breakthrough inventions due to decreased

[18] The American Inventors Protection Act (P.L. 106-113), which limits publication delay to 18 months unless application is filed only within the boundary of the US, was enacted on November 29, 1999, and took effect on November 29, 2000.

value of patent protection (Aoki and Spiegel 2001). A natural policy question from this debate is what would happen if the publication lag is reduced to 12 months or even zero month, or equivalently what is the rationale of the existence of the publication lag itself? Our model provides an explanation of why the publication lag, even if it is very short, is necessary.

Consider an easy second innovation for which infinite potential competitors (including the first inventor) can immediately make it once the first invention is revealed. If the first patent is published without any lag, firms will immediately jump into the race and potential rent is completely dissipated. On the other hand, if the first patent is kept unpublished for a limited period (say, 18 months in the current U.S. law), then the first patent holder has time to exclusively develop the second innovation as a monopolist. For a low cost (say, $0 < k < k_1$, in equation (8)), the second innovation is made immediately at $t = 0$ and rent dissipation is avoided when the second innovation is monopolistic through a limited publication lag. We can argue that the publication lag can be interpreted as a means of reducing common pool problem by providing a temporary monopoly power to the first patent holder. If the cost of the second innovation is high ($k > k_1$), the second innovation is delayed under monopoly and social welfare may be reduced with a publication lag. However, this welfare loss from delayed innovation can be mitigated if the publication lag is shortened (say, from 18 months to one day).

In an environment of asymmetric information where government does not know the size R&D cost for the second innovation, policymaker can improve social welfare by adopting a short publication lag. If the R&D cost is cheap so that the second innovation is instantaneous, the publication lag avoids the common pool problem without delaying the innovation. On the other hand, if the second innovation is not made immediately after the first patent, it signals that the R&D cost is not cheap enough to induce an instantaneous second innovation. But, the welfare loss due to delayed innovation can be minimized by making the publication lag very short.[19]

5.3. UNCERTAIN COST

Previous analysis showed that the implication of patent life on social welfare depends on the exact level of R&D cost for the second innovation. Policymakers rarely observe the exact level of R&D cost in practice, and they set a single patent life based on the expected cost. Assuming the distribution of k as a function $G(k)$, the social welfare functions under competition and under monopoly are, respectively,

$$S_c = \frac{v}{r}\left\{\int_0^{k_2}\left[\alpha + (1-\alpha)e^{-rT}\right]dG + \int_{k_2}^{k_3}\left[\alpha(1-k)e^{-rT} / \left(e^{-rT} + k - (1-\alpha)\right)\right]dG\right\}$$

$$S_m = \frac{v}{r}\left\{\int_0^{k_1}(1-k)dG + \int_{k_1}^{k_3}(1-k)e^{-rT}dG\right\}.$$

The shape of the distribution function determines the level of optimal patent life and social welfare. If the distribution is skewed to the left (i.e., low cost), a short, finite patent life may maximize social welfare. However, if the cost is normally distributed so that the cost is likely to be in the intermediate level, then the choice of the patent life is delicate, as was shown in figure 3. As an example, if we assume a uniform distribution function, the social welfare functions are (see appendix for detailed derivations)

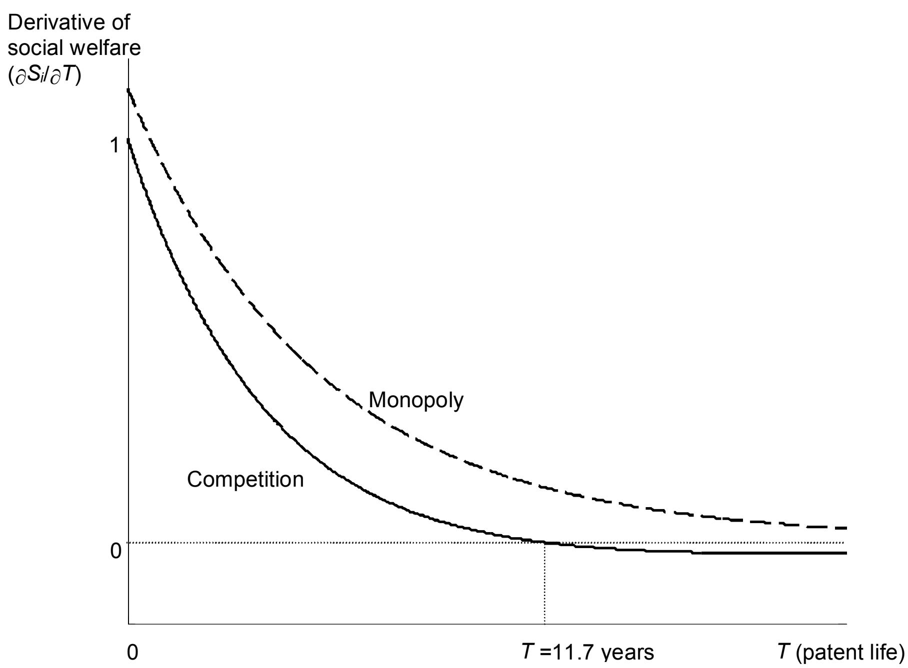
[19] Of course, this argument assumes that the first invention has already been made and patented. The strategic patenting behavior of the first inventor under different rules is beyond the scope of this paper.

$$S_c = \frac{v}{r}\left\{\alpha(1-\alpha)(1-e^{-rT}) + (1-2\alpha)e^{-rT}(1-e^{-rT}) + \alpha rTe^{-rT}(\alpha+e^{-rT})\right\}$$

and $$S_m = \frac{v}{2r}\left[1-\left(\alpha+e^{-rT}\right)^2 + \alpha e^{-rT}(2-\alpha)\right].$$

Equation (A6) in appendix shows that under monopoly the longer the patent life the higher the social welfare. However, the sign of $\partial S_c/\partial T$ for a competitive case is ambiguous depending on the level of patent life. Using the same parameter space as above, the derivatives of social welfare with respect to the patent life T are illustrated in figure 7. Figure 7 shows that the optimal patent life under competition is 11. 7 years.

Figure 7--Derivative of social welfare and optimal patent life



6. CONCLUSION

In this paper, we have examined the role of the patent protection when granted for an innovation that is an essential input to further innovation in a research sequence. In a highly stylized two-stage model with an inelastic first invention, we have found a richness in the implications of patenting not evident in one-stage models or models restricted to two firms. We first show that a long patent life may not hinder subsequent innovation when the R&D cost of the innovation is not sufficiently high, in contrast to the conclusions of existing studies. The extra revenue from a longer patent life can dominate the longer stream of royalty payment associated with a longer patent life.

The analysis also reveals benefits from patent life limitation quite distinct from those related to distortion in consumption (Nordhaus) or rent-seeking in innovation (Barzel, Wright 1983, 1984). For innovations where the gross profit margin is modest, the limit on patent life can induce subsequent innovation that would be precluded under infinite patent life. At the optimal patent life, the second innovation yields zero net profit and occurs on expiration of the first patent. But if the patent life is set too long, the cost in delay of innovation is moderated in a polar competitive innovation market because the subsequent innovation begins before the patent life expires. The patent life limitation acts as a means of (partial) commitment against excessive exploitation by the holder of the invention essential to further innovation. In addition, a patent on the first invention and the requirement for a licensing agreement can be welfare improving by limiting excessive rent dissipation for the second innovation when the second innovation is highly profitable.

Another implication of this study is that social welfare is in general not sensitive to patent life and a finite patent system is self-selective due to firms' ability to adjust the timing of investment. As long as the patent life is set long enough to induce innovation, the cost of suboptimal level of patent life is minor. If the second innovation is monopolistic, rent dissipation due to competitive race for patents can be avoided and social welfare is greater than the case of competition if the second innovation is cheap. This implies that if the first inventor is as efficient as the competitors, endowing the first inventor with monopoly power in the second innovation might be welfare improving even if there exist many competitors (Kitch).

The assumptions we have made here are extreme, in order to facilitate the analysis and exposition, but they are not crucial for the qualitative results. But we believe, based on numerical results not reported here, that if we introduce the possibilities of duplication in research, less responsive market entry by second-stage researchers, finite elasticity of supply of research, or finite elasticity of demand for the final product, or economically responsive first-period research, the model would yield similar qualitative conclusions. Introduction of a lag between research effort and results would lengthen optimal patent length in some cases, but would not otherwise change our findings on the general advantage of finite over infinite patent life in the patenting of innovations that are themselves essential research inputs.

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