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SHOULD WE WAIT FOR A NEW TECHNOLOGY?

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This paper shows the mechanism of technology dissemination when two rival firms decide timings of either international adoption or domestic imitation for a newly available technology. The set of optimal strategies for a dynamic Nash game includes immediate (but, not delayed) simultaneous international adoption; and sequential decisions for technology dissemination. The paper also illustrates that there is no technology adoption and whereby this waiting problem is due to the usual structure of contingent profits and costs of dissemination in a duopolistic market. Therefore the paper explains that the rivalry and strategic behaviors cause a slow and incremental process for dissemination of emerging technologies.

JEL Classification: D43, O33
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I. INTRODUCTION

Invention and innovation plays an important role in persistent long-run economic growth since the industrial revolution. Since most countries in the world adopt and use technologies rather then invent or innovate them, the benefit of a new or improved product or production process, however, accrues through its adoption and imitation or dissemination to the country until it is supplanted. In order for a country to benefit from invention and innovation, there must be incentives for firms adopt emerging technologies. This paper examines the effect of international technology adoption and its domestic imitation when the new technology has been perfected in international R&D markets. We analyze the

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extent and timings of both technology dissemination processes when more than one rivalry firm determine strategically their optimal adoption and imitation in a small open economy.

Empirical observations including Rosenberg and Birdzell (1986) and Mokyr (1990) suggest that dissemination of a new technology is a slow and incremental process and that firms do not adopt a new technology simultaneously. There are mainly four classes of works to explain such deterrence of technology dissemination. Firstly, Stenbacka and Tombak (1994), Hendricks (1992), and Jensen (1992) attribute this to market uncertainties about, for example, profitability; investment cost; a time lag between adoption and its implementation; and innovative capacity of rivals. Secondly, Farzin *et al.* (1998), Purvis *et al.* (1995), Dixit and Pindyck ((1994) examine irreversibility with technological shocks as a source of the slow imitation of a new technology. Thirdly, Fudenberg and Tirole (1985) and Riordan (1992) analyze that preemptive strategies can deter technology dissemination. Fourthly, as in Kamien and Schwartz (1972), Reinganum (1981) and Katz and Shapiro (1987), the present paper focuses that the rivalry of international adoption and domestic imitation affect the delay of timings of international technology adoption for a new technology (refer to up-to-date survey, Reinganum (1989) and Bridges *et al.* (1991)).

We consider a small open economy where there are two *ex ante* identical firms in an industry for a given new advanced technology available from international markets. Two rival firms are assumed to be operating the current best technology. When a profit-enhancing new technology is available to the firms, each firm can be the adopter of the advanced technology, paying a higher adoption cost and expecting a higher future profit stream. Or, the firm can be an imitator of the available technology in the domestic market, paying a lower imitation cost and thereby expecting a lower future profit stream. Of course, domestic imitation by a firm can occur only after the other firm buys the new technology at some earlier time. In this simple model of technology dissemination, essentially following Reinganum (1981), Fudenberg and Tirole (1985), we are concerned with the game-theoretical analysis on the nature of international technology dissemination when a firm decides to be an imitator in the domestic market in the presence of positive externality effects.

This paper presupposes that the mechanism for international technology adoption is different from the one for domestic imitation. Even though technology is non-rivalry and non-exclusive, perfect non-exclusion is not observed in international markets for various reasons including the difference in general-purpose-knowledge. Hence, technology dissemination in the international market is likely to require a means of transferring or licensing, which often involves expensive adoption cost.[1]

[1] Lee and Park (2000) reports two empirical findings for asymmetry between domestic and foreign technology dissemination including Kindelberger's (1995) survey on European experiences in technology diffusion among countries.

The closest work to ours is the insightful paper by Kamien and Schwartz (1972) and Reingnum (1981), which addresses the questions of equilibrium timing of R&D when there is a rival for innovation and limitations. The present paper, however, deviates from theirs in five main aspects: First, rather than analyzing R&D competition, it emphasizes a two-person game at the market for technology adoption and imitation. As in Stenbacka and Tombak (1994) there are two potential buyers for a new technology from a foreign market and leads to strategic decisions. Second, there are *ex post* heterogeneous firms and this paper thereby is concerned with the timings of international adoption and domestic imitation in the presence of the beneficiary firm for a newly arrived technology in its own economy. Third, it generalizes a usual cost function of imitation in the literature by assuming the function to be a function of both the timing of international and domestic dissemination. That is, our paper also generalizes Reinganum (1981) by imposing that two firms face two different costs and contingent profits at the market conditions for acquisition of the new technology. Forth, it shows a mechanism of seeking for all possible outcomes, including a waiting game problem permitting possibility of no introduction of a new technology to be optimal strategies, which was recognized, but analyzed by Kamien and Schwartz (1972) and Reingnum (1981). Finally, the optimal timings of strategic decision depend not only on the cost reductions for dissemination over time, but also on the flow of profits, relying on each firm's market condition.

One of main contributions of this paper is to determine an open-loop equilibrium timing for strategic decisions in the presence of exogenous technological progress. Contrary to the model in Stenbacka and Tombak (1994), we focus on strategic timing decisions and thus its *ex post* position to be either adopter or imitator for a newly arrived technology, despite the facts that information is perfect and firms are *ex ante* identical. This paper also shows that when domestic imitation effect is strong enough, there is no strategic timing equilibrium even under perfect information.[2] Intuitively, the domestic imitator follows the international adopter too soon, lessening the profit opportunity to be a first mover in international. That is, even though moving first gives some positive benefit for a firm, moving second gives more benefits for the firm, so, each firm wants the other firm to move first, resulting in a socially inefficient waiting game problem in the technology dissemination game. It suggests that a proper government policy can stimulate technology dissemination at monopolistically competitive markets.

This paper processes as follows. Section 2 builds a dynamic model for Nash timing problem in technology dissemination. We characterize the dynamic Nash equilibrium for optimal international adoption and domestic imitation of a new

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[2] Notably, under an uncertain environment, Fudenberg and Tirol (1985) show a continuum of equilibria.

technology in Section 3. Section 4 specifies the cost functions for adoption and imitation in order to demonstrate the waiting game problem. Concluding remarks follow in Section 5.

II. THE BASIC MODEL

In a small open economy,[3] an industry composes of two identical rivalry firms. Each of these two firms, say firm 1 and firm 2, is assumed to be a Cournot-competitor with each other, facing given market demand.[4] Initially these two firms are using the current best technology available, the old technology, denoted by o. At time $t=0$, a profit-enhancing advanced technology,[5] the new technology, denoted by n, is available to both firms. Each firm has two alternative actions regarding the advanced technology: (1) buying the technology from the international market, paying the international adoption cost $c(t)$, which is the function of the adoption time t at which the firm purchase the technology from the foreign seller; (2) waiting until the rival firm buys the advanced technology from the international market; and imitating it at some later time by paying the domestic imitation cost $d(s;t)$, where t is the international adoption time by the other firm and s is the time elapsed between the domestic imitation and the international adoption. That is, the actual imitation time occurs at $t+s$.

We will make the following assumptions regarding the international adoption cost and the domestic imitation cost. Similarly to the expenditure function for R&D in Kamien and Schwartz (1972) and Reinganum (1981, 1989) and many others in the R&D literature, the cost of international adoption and domestic imitation is a function of time. This cost also is a one-shot sunk cost and will be borne by the disseminating firm at time t.

First, we assume that the adoption cost function is a positive and strictly decreasing convex function of the adoption time.

ASSUMPTION 1. $c(t)>0$; $c'(t)<0$; $c''(t)>0$, for all $t\in[0,\infty]$.[6]

This adoption cost is considered as the price of the new technology in the international market, referring to Lee and Park (2000) in the economy with one buyer and one seller. This assumption is also equivalent to those in Quirmbach (1986) and Fudenberg and Tirol (1985). For example, these cost functions:

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[3] Lee and Park (2000) generalize to economies where technology adoption is decided by strategic bargaining between a seller and buyer in international technology markets.

[4] This technology dissemination game is similar to an R&D game as in Kamien and Schwartz (1982) and Reinganum (1987).

[5] Such formulation for technology is equivalent to one for cost reduction for a new technology in our model.

[6] Note that $c'(t)$, $c''(t)$ is the first and second order derivative in term of t, respectively.

$c(t)=ae^{-kt}$; $c(t)=\frac{k}{t}$, $k>0$, satisfy the above assumption.

Second, we impose conditions on the domestic imitation cost. This imitation cost function generalizes the constant cost of imitation in Quirmbach (1986) and Katz and Shapiro (1987). The role of this assumption will be discussed below.

ASSUMPTION 2. For each t, $d(s;t)>0$; $d^{s}(s;t)<0$; $d^{ss}(s;t)\geq 0$, for all $s\in[0,\infty]$;[7] and for each s, $d^{t}(s;t)<0$, $d^{tt}(s;t)\geq 0$, $d^{ts}(s;t)=d^{st}(s;t)\geq 0$ for all $t\in[0,\infty]$.

At the first part of this assumption, the domestic imitation cost is a decreasing convex function of the time elapsed between domestic imitation and international adoption. The latter part of the assumption says that this cost function is also a decreasing convex function in term of the international adoption time. This concavity in addition to technical assumption $d^{ts}(s;t)=d^{st}(s;t)\geq 0$ is required for ensuring existence of optimal strategy.[8]

A firm has adopted once the advanced technology, and then the cost for the other firm to acquire the technology by domestic imitation is less than the international adoption cost. It suggests that technology bears the public good natures: non-exclusive and non-rivalry.[9] That is,

ASSUMPTION 3. $d(s;t)<c(t+s)$ for all s, $t>0$; and $d(0;t)=c(t)$ for all t.

This is equivalent to saying that the adopting firm has a choice between domestic imitation and international adoption for acquiring the technology. This assumption is standardized as in Fudenberg and Tirol (1985). An example of such a domestic imitation cost function satisfying Assumption 2 and 3 is $d(s,t)=ae^{-(kt+hs)}$, k, $h>0$.

There are four possible states for the industry regarding the technology each firm uses,

$$(o,o),\ (n,o),\ (o,n),\ (n,n),$$

where the first coordinate is for firm 1's technology; and the second coordinate is for firm 2's technology - either the old technology o or the new technology n.

At time $t=0$, each firm must determine when to buy or adopt the new

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[7] Note that $d^{\alpha}(s;t)$ is the first partial derivative with respect to argument α where $\alpha=s,t$; and $d^{\alpha\beta}(s;t)$ denote a second partial derivative in terms of arguments α,β where $\alpha,\beta=s,t$.

[8] Notice that we need not assume the cost function to be jointly concave in s and t.

[9] Recently, this idea is widely used in the endogenous growth theory (see, for example, Romer (1986) and Lucas (1988)).

technology, maximizing the expected discounted net profit. This profit is a function of the other firm's choice and each firm is assumed to be a Nash competitor with the other. Assuming that the market demand is stationary over time the profit allocation generated by Cournot competition is constant over time in each of above four states. Let $\pi(x;y)$ be a profit per period for a firm when the firm chooses the technology x, $x=0, n$, when the other firm chooses technology y, $y=o, n$. This is, the profit for each firm depends on how the other chooses its technology. For given $(\hat{x}, \hat{y})$, $\hat{x}, \hat{y}=o, n$, the profit per period for both firms is $(\pi(x;\hat{y}), \pi(y;\hat{x}))$ at the state (x, y) where $x, y=o, n$.

Now, we assume profit for each state and their relations as followings:

ASSUMPTION 4. Profit for all possible states has the following rank and property:

$$\pi(n;o)>\pi(n;n)>\pi(o;o)>\pi(o;n)>0;\ \pi(n;o)-\pi(o;o)>\pi(n;n)-\pi(o;n).$$

This profit function subsequent to its own technology generalizes one in the literature, for example, Quirmbach (1986), and Katz and Shapiro (1987). This assumption states that the increase in profit for the international-technology adopting firm is greater than the increase in profit for the domestic-technology imitating firm.[10] The second inequality can be justified by recognizing that a new technology leads higher profit than an old technology to both firms.[11] However, the firm's profit for technology adoption is greater when the rival firm chooses not to do the same. The second part of assumption insures the profitability of a new technology in the domestic market. That is, the configuration of profits incorporates not only the way in which the new technology offers high profits for the both, but also the nature of competition determines the relative position for each firm in the market.

Let t_i and t_j be the time of action of either buying or adopting by firm i, $i=1, 2$, and firm $j\neq i$, $j=1, 2$, respectively. The interest rate is represented by r. Then the firm i's discounted net profit $V_i(t_i;t_j)$ of moving at time $t=t_i$, given firm j's move at $t=t_j$, is the following: When $t_i\leq t_j$;

$$V_i(t_i;t_j)= \tag{1.1}$$
$$\int_{t_i}^{t_j} e^{-rt}[\pi(n;o)-\pi(o;o)]dt+\int_{t_j}^{\infty} e^{-rt}[\pi(n;n)-\pi(o;o)]dt-e^{-rt_i}c(t_i).$$

However, when $t_i>t_j$,

[10] This assumption can be shown to be satisfied when a production cost function is of constant marginal cost and the market demand is linear.

[11] We realized that the full justification for this assumption requires for specifying the demand and the nature of competition for their outputs.

$$V_i(t_i;t_j)= \tag{1.2}$$
$$\int_{t_j}^{t_i} e^{-rt}[\pi(o;n)-\pi(o;o)]dt+\int_{t_i}^{\infty} e^{-rt}[\pi(n;n)-\pi(o;o)]dt-e^{-rt_i}d(t_i-t_j;t_j).$$

Notice that $V_i(t_i;t_j)$ are continuous at $t_i=t_j$ since $d(0;t)=c(t)$ for all t. But they are not differentiable at that point.

For an analytical simplicity we will exclude the possibility that a firm will not adopt the technology at all. This can occur if the adoption cost or the imitation cost is too high to guarantee the firm a positive value from the technology adoption or imitation. That is, we assume that, given t_j, there exists some t_i such that $V_i(t_i, t_j)\geq 0$, where $i, j=1, 2$.

Ⅲ. THE OPTIMUM TIMING FOR THE NEW TECHNOLOGY

The timing problem for the new technology can be summarized in a game theoretic framework: The game is represented by $\Gamma=\{(1, 2), \Theta, V\}$, where (i) there are two players, firm 1 and firm 2; (ii) the strategy space is $S=S_1\times S_2\in\Theta$ where $S_i=[0, \infty]$ for $i=1, 2$ and the pure strategy for player i is $t_i\in S_i$; (iii) the payoff function V_1, V_2 is given by Equations(1.1)-(1.2).

DEFINITION 1. The best response for firm i to t_j is

$R_i(t_j)=\inf\{t_i\in S_i : V_i(t_i, t_j)\geq V_i(t_i', t_j)$ for all $t_i'\in S_i$, (t_i, t_j), (t_i', t_j) $\in\Theta\}$.

The mapping $R_i;S_j\rightarrow S_i$ is i's best response function.

DEFINITION 2. A strategy pair (t_i^*, t_2^*) is a Nash equilibrium for the game Γ if (i) $t_1^*\in S_1$, $i=1, 2$; (ii) $V_1(t_1^*;t_2^*)\geq V_1(t_1;t_2^*)$, for all $t_1\in S_1$, and $V_2(t_2^*;t_1^*)\geq V_2(t_2;t_1^*)$ for all $t_2\in S_2$. That is, (t_1^*, t_2^*) is a Nash Equilibrium if $t_1^*=R_1(t_2^*)$ and $t_2^*=R_2(t_1^*)$.

Hence, the best response function for firm i, $i=1, 2$, to firm j, $j(\neq i)=1, 2$, is

$$R_i(t_j)=\inf[\arg\max_{t_i} V_i(t_i;t_j)]=\inf\{\arg\max_{t_i}[\max_{t_i\in[0, t_j]} V_i(t_i;t_j), \max_{t_i\in[t_j, \infty]} V_i(t_i;t_j)]\}.$$

LEMMA 1. If a firm moves first, i.e. buys the new technology, then the firm's optimal adoption time is either 0 or t^* independently with the other firm's imitation time. Furthermore, the optimal adoption time $t^*\neq 0$ satisfies

$$\pi(n;o)-\pi(o;o)=rc(t^*)-c'(t^*). \tag{2.1}$$

However, when $t^* = 0$,

$$\pi(n;o) - \pi(o;o) > rc(0) - c'(0). \tag{2,2}$$

PROOF. Without loss of generality, consider the case in which firm 1 moves first, that is $t_1 < t_2$. Suppose $t_1^* = t^*$ is optimal for the first mover, firm 1. Then, $t^* < t_2$. Also, firm 1's problem is

$$\max_{t_1 \in [0,\, t_2]} V_1(t_1; t_2)$$
$$= \int_{t_1}^{t_2} e^{-rt}[\pi(n;o) - \pi(o;o)]dt + \int_{t_2}^{\infty} e^{-rt}[\pi(n;n) - \pi(o;o)]dt - e^{-rt_1}c(t_1).$$

The first order condition is

$$\frac{dV_1(t_1;t_2)}{dt_1} = -e^{-rt_1}[[\pi(n;o) - \pi(o;o)] - [rc(t_1) - c'(t_1)]].$$

It is clear that the second order condition for optimality holds under Assumption 1. Since $t^* < t_2$, the solution is not binding by t_2. Thus the above equation for $\frac{dV_1(t_1;t_2)}{dt_1}$ implies that the optimal adoption time $t^* \neq 0$ satisfies $\pi(n;o) - \pi(o;o) = rc(t^*) - c'(t^*)$. However, when $t^* = 0$, $\pi(n;o) - \pi(o;o) > rc(0) - c'(0)$. Therefore, since the RHS of Equation (2) is strictly decreasing in t_1, t^* is unique and independent of t_2. **Q.E.D.**

Note that Equations (2.1) and (2.2) are analogous to Equation 3 in Katz and Shapiro (1987). The LHS of Equation (2.1), $\pi(n;o) - \pi(o;o)$,[12] represents the forgone profit due to the delay of the international adoption by one period, and the RHS of the same equation, $rc(t^*) - c'(t^*)$, represents the sum of the saved service flow of the imitation cost $c'(t)$ and the cost reduction $rc(t)$ due to waiting one more period. At optimum in the interior the marginal cost and the marginal benefit should be the same when the adoption is chosen at a non-zero finite time. Related to capital investment theory, the first term on the RHS also corresponds to the capital gain of not spending earlier.

LEMMA 2. When a firm moves second, i.e., it is the domestic adopter of the new technology, the optimal imitation lag for the firm is $s^*(t) \neq 0$, given the international adoption time t by the rival firm, such that

[12] In our model $\pi(n;o) - \pi(o;o)$ can be interpreted as an "imitation incentive". Similarly, Katz and Shapiro (1987) refer to $\pi(n;o) - \pi(o;o)$ as a "stand-alone incentive" in the context of dynamics R&D competition.

$$\pi(n;n)-\pi(o;n)=rd(s^*(t);t)-d^s(s^*(t);t). \tag{3.1}$$

On the other hand, when $s^*(t)=0$,

$$\pi(n;n)-\pi(o;n)>rd(s^*(t);t)-d^s(s^*(t);t). \tag{3.2}$$

Furthermore the imitation lag will be shortened as the adoption time is delayed, i.e., $\frac{ds^*(t)}{dt}<0$.[13]

PROOF. Without loss of generality, consider the case where firm 1 moves second, i.e., $t_1=t_2+s$, $s>0$. This firm's problem is as the following:

$$\begin{aligned}&\max_{s\in[0,\infty]} V_1(t_2+s;t_2)\\ &=\int_{t_2}^{t_2+s} e^{-rt}[\pi(o;n)-\pi(o;o)]dt+\int_{t_2+s}^{\infty} e^{-rt}[\pi(n;n)-\pi(o;o)]dt\\ &\quad -e^{-r(t_2+s)}d(s;t_2)\end{aligned}$$

The first order condition for this optimal timing for domestic imitation is

$$\frac{\partial V_1(t_2+s;t_2)}{\partial s}=-e^{-r(t_2+s)}[[\pi(n;n)-\pi(o;n)]-[rd(s;t_2)-d^s(s;t_2)]].$$

Therefore, we have Equations (3.1) and (3.2). Clearly, the second order condition for a maximum is also satisfied under Assumption 2.

Now, under Assumption 2, using the implicit function theorem on Equations (3.1) and (3.2), we get $\frac{ds^*(t)}{dt}=[rd^s(s;t)-d^{ss}(s;t)]^{-1}[-rd^t(s;t)+d^{st}(s;t)]$ <0 for all t. **Q.E.D.**

Analogous to Equations (2.1) and (2.2), Equations (3.1) and (3.2) indicate that the benefit of domestic imitation is large enough, with respect to the sum of the cost reduction for a waiting period and the saved cost flow that dissemination occurs immediately after a new technology is available in the economy.

Lemma 1 and Lemma 2 establish the set of possible Nash timing equilibria in pure strategies as follows: $(0, 0)$; $(0, s^*(0))$; $(s^*(0), 0)$; (t^*, t^*); $(t^*, t^*+s^*(t^*))$; $(t^*+s^*(t^*), t^*)$. In particular, the following lemma excludes the non-zero symmetric equilibrium:

LEMMA 3. There is no non-zero symmetric Nash equilibrium in pure strategies,

[13] This property is also investigated in Fudenberg and Tirole (1985) and Stenbacka and Tombak (1994). However, their results depend on the role of ex ante a leader and follower.

i.e., (t^*, t^*), is not an equilibrium.

PROOF. It suffices to show that, for given $t^*>0$, $s^*(t^*)>0$. Suppose $s^*(t^*)=0$. We have $\pi(n;n)-\pi(o;n)\geq rd(0;t^*)-d^s(0;t^*)>rc(t^*)-c'(t^*)=\pi(n;o)-\pi(o;o)$. The first inequality is due to Lemma 2. Assumption 2 yields the second inequality: That is, $c'(t)>d^s(0;t)$ since for all t $c(t)=d(0;t)$; and $c(t+s)>d(s;t)$ where $s\neq 0$. The inequality: $\pi(n;n)-\pi(o;n)>\pi(n;o)-\pi(o;o)$ contradicts to Assumption 4. **Q.E.D.**

This lemma excludes the possibility of *ex post* identical firms at the strictly positive time once a new technology is introduced. Hence, contrary to Stenbacka and Tombak (1994), strategic actions of both firms will distinctively identify their position of in the technology dissemination game. Under the similar properties of these cost functions the asymmetric equilibrium of optimal dissemination of a new technology was found in Reingnum (1981) and Quirmbach (1986).

The following lemma shows that a firm prefers moving first, that is, buying the new technology at a foreign market at time t^* if and only if there exists the critical value $\tilde{t}$ where the other firm adopts this technology later than $\tilde{t}(>t^*)$.

LEMMA 4. Given s^*, $t^*\geq 0$, there exists a unique $\tilde{t}$ such that

$$V_1(t^*;t)>(=<)V_1(t+s^*(t),\ t) \quad \text{as} \quad t>(=<)\tilde{t}.$$

PROOF. Suppose firm 2 moves at time t. Then the difference in the net profit between moving first and moving second for firm 1 is given by $\Delta(t)\equiv V_1(t^*;t)-V_1(t+s^*(t);t)$. By Lemma 3, $\Delta(t^*)<0$. Also notice that

$$\begin{aligned}\lim_{t\to\infty}\Delta(t)=\int_{t^*}^{\infty}[\pi(n;o)-\pi(o;o)]e^{-ru}du-e^{-rt^*}c(t^*)\\ -\lim_{t\to\infty}\left[\int_{t}^{t+s^*(t)}[\pi(o;n)-\pi(o;o)]e^{-ru}du\right]\\ +\lim_{t\to\infty}\left[\int_{t+s^*(t)}^{\infty}[[\pi(n;n)-\pi(o;o)]e^{-ru}-e^{-r(s^*(t)-t)}d(s^*(t);t)]du\right]>0.\end{aligned}$$

Therefore there exists some sufficiently large number T such that $\Delta(T)>0$. Since $\Delta(t)$ is a continuous function in t, we can use the intermediate value theorem to conclude that there exists a $\tilde{t}$, such that, $T>\tilde{t}>t^*$ which satisfies $\Delta(\tilde{t})=0$.

Now it is clear that that $\Delta(t)$ is a strictly increasing function of t. That is, by using the envelope theorem, we have: $\frac{d}{dt}\Delta(t)=\frac{d}{dt}V_1(t^*;t)-\frac{d}{dt}V_1(t+s^*$

$(t);t)>0$. Therefore there is unique $\tilde{t}$ that holds the Lemma. **Q.E.D.**

Now, we can describe the best response function each firm as follows. First note that $\pi(n;o)-\pi(o;o)<rc(0)-c'(0)$ implies $\pi(n;n)-\pi(o;n)<rd(0;0)-d^s(0;0)$, which can be shown easily under Assumptions 3 and 4. Therefore, by Lemma 1-4, we need to consider only three cases for the best response function as below:

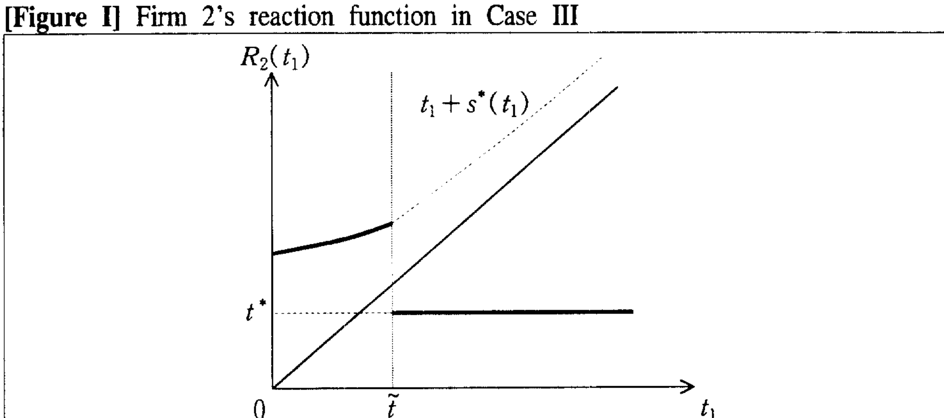
CASE I. Suppose $\pi(n;o)-\pi(o;o)\geq rc(0)-c'(0)$ and $\pi(n;n)-\pi(o;o)\geq rd(0;0)-d^s(0;0)$. When $t_j\geq 0$, $R_i(t_j)=0$ for all $i,j=1,2$ $i\neq j$.

CASE II. Suppose $\pi(n;o)-\pi(o;o)<rc(0)-c'(0)$ and $\pi(n;n)-\pi(o;o)<rd(0;0)-d^s(0;0)$. When $t_j\geq\tilde{t}$, $R_i(t_j)=0$ for all $i,j=1,2$, $i\neq j$. When $t_j<\tilde{t}$, $R_i(t_j)=s^*(t_j)$, for all $i,j=1,2$, $i\neq j$.

CASE III. Suppose $\pi(n;o)-\pi(o;o)<rc(0)-c'(0)$. When $t_j\geq\tilde{t}$, $R_i(t_j)=t^*$ for all $i,j=1,2$, $i\neq j$. When $t_j<\tilde{t}$, $R_i(t_j)=t_j+s^*(t_j)$ for all $i,j=1,2$, $i\neq j$.

Figure I illustrates for Case III that firm 2's optimal time decision in Nash competition is along $s^*(t_1)$-curve as t_1 moves from 0 up to $\tilde{t}$; and at that point jump down to t^* and stays there as t_1 increases from $\tilde{t}$. First, notice that $R_2(\tilde{t})\neq t_1+s^*(\tilde{t})$, but $R_2(\tilde{t})=t^*$ by the inequality condition in Case III. Second, it is clear that $R_2(t_1)$ is not continuous at $t_1=\tilde{t}$ not only because $R_2(\tilde{t})\neq\tilde{t}$ by Lemma 3, but also because Lemma 2 (i.e., $\frac{ds^*(t)}{dt}<0$, $s^*>0$, and thus $\frac{\partial V(\tilde{t}(s^*)+s^*;\tilde{t}(s^*))}{\partial s^*}>0$) and Lemma 4 (i.e., when $s^*=0$, $V(t^*;\tilde{t})>V(\tilde{t};\tilde{t})$ since t^* is optimal for given $\tilde{t}$), contradicting to the continuity of $R_2(\tilde{t})$ at $\tilde{t}$, in which there exists $\varepsilon>0$ such $t^*=R_2(\tilde{t})=t^*+\varepsilon$.

[Figure I] Firm 2's reaction function in Case III



The following proposition characterizes the set of Nash equilibria in pure strategy.

PROPOSITION 1. The timing problem $\Gamma=\{(1,2),\Theta,V\}$ has following solutions in a small open economy:

1. In Case 1, there is the only Nash equilibrium $\{(0,0),(0,0)\}\in\Theta\times\Theta$.
2. In Case II, there are Nash equilibria in pure strategies if and only if $s^*(0)\geq\tilde{t}$. Hence, if exist, the set of Nash equilibria is $\{(0,s^*(0)),(s^*(0),0)\}\in\Theta\times\Theta$.
3. In Case III, there are Nash equilibria in pure strategies if and only if $t^*+s^*(t^*)\geq t^*$. Hence, if exist, the set of Nash equilibria is $\{(t^*,t^*+s^*(t^*)),(t^*+s^*(t^*),t^*)\}\in\Theta\times\Theta$.

PROOF. Suppose the first mover's optimal technology adoption time from the international market is t^*. We consider the most general Case III. Lemma 1 implies that t^* is independent of the second mover's domestic technology imitation time. Since $\pi(n;o)-\pi(o;o)<rc(0)-c'(0)$ implies $rd(0;0)-d^s(0;0)>\pi(n;n)-\pi(o;n)$, the second mover's optimal imitation time, given the adoption time t^* is $t^*+s^*(t^*)$. Therefore, by Lemma 4, only candidates for Nash competition will move first if and only if the other firm moves later than $\tilde{t}$. Hence, the equilibria will occur if and only if $t^*+s^*(t^*)\geq\tilde{t}$.

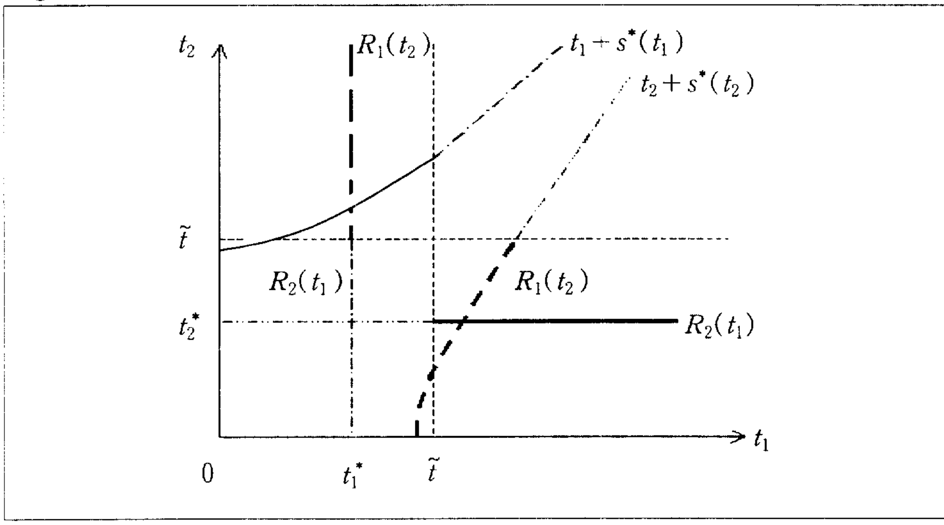
In the case II, Lemma 1 implies that the first mover's optimal adoption time is $t^*=0$; that represents the immediate international adoption. Since $\pi(n;n)-\pi(o;o)<rd(0;0)-d^s(0;0)$, the second mover will adopt the new technology in the domestic market at $s^*(0)$. Finally, by Lemma 4, the equilibria will occur if and only if $s^*(0)>\tilde{t}$.

For Case I, it is clear that Lemmas 1 and 2 imply that immediate adoption is optimal for international technology adoption and thus immediate imitation is optimal. **Q.E.D.**

The proposition shows that immediate technology adoption is the only symmetric solution in a non-competitive market. Note that Reinganum (1989) and Katz and Shapiro (1987) conjecture this possibility in models of R&D competition. Unlike our result, they focus only on the interior solution for positive timing for actions as in Case III. Therefore, this proposition generalizes the literature by explicitly characterizing the corner solutions. Case II is in fact the special case of Case III. Both cases show the existence of the *ex post* heterogeneous firms, whereas Stenbacka *et al.* (1994) assumes *ex ante* heterogeneous firms.[14]

[14] Since this model is a partial equilibrium analysis and there exists the public-good nature of technology, we can only conjecture welfare ranks for the above cases. That is, the immediate, simultaneous adoption (Case I) is not necessarily yields higher social welfare than sequential adoption and imitation (Case II or III). It is reasonable to guess that the social welfare for Case III can be higher than Case III.

[Figure 2] Nash Solutions for Case III



Case III is illustrated in Figure 2 below. In Figure 2, where $t^*+s^*(t^*)\geq\tilde{t}$, the best response functions interest at $(t^*, t^*+s^*(t^*))$ and $(t^*+s^*(t^*), t^*)$, and they are two Nash equilibria. Clearly, Case II is when $t^*=0$.[15]

Ⅳ. THE WAITING GAME PROBLEM: AN EXAMPLE

In the previous section we found the set of Nash equilibria, if exist, in the economy for technology adoption and imitation. We now specify the adoption cost function and the imitation cost function to illustrate properties of those equilibria. Later of the section, we also demonstrate the waiting problem of technology dissemination.

Let a cost function for adoption for a new technology be $c(t)=ae^{-kt}$, where $a>0$ and $k>0$. This function satisfies Assumption 1, i.e., $c'(t)<0$ and $c''(t)>0$. We also specify a cost function for technology imitation: $d(s;t)=ae^{-kt}e^{-hs}$, where $h>k$. Note that the imitation cost function is exponentially decreasing function of the time elapsed between the imitation time and the adoption time, with the rate of exponential coefficient h. It can be considered that the coefficient $h-k$ represents the degree of the domestic diffusion speed of the technology. Given k, the greater h the faster domestic diffusion, and thus the lower the imitation cost. In sum, this imitation cost function satisfies Assumption 2.

Together with the adoption cost function, the imitation cost function also

15 A referee pointed out an interesting question for selecting one of Nash equilibria, yet rational expectation models convey the similar feature. In order to dealing with this question, we need to introduce more structures and behavioral assumptions.

satisfies Assumption 3. It is easy to check that Assumption 3 holds, i.e., for all $t \geq 0$, since $ae^{-kt}e^{-hs} < ae^{-k(t+s)}$ for all $h > k$, $d(s;t) < c(s+t)$; and $d(0;t) = c(t)$.

Optimal Technology Adoption and Imitation Time for a New Technology

Firm 1's problem as a first mover is as following: $\max_{t_1 \in [0, t_2]} V_1(t_1; t_2)$, where $V_1 = \int_{t_1}^{t_2} e^{-rt}[\pi(n;o) - \pi(o;o)]dt + \int_{t_2}^{\infty} [\pi(n;n) - \pi(o;o)]dt - ae^{-(k+r)t_1}$. Here we maintain Assumption 4 for configuration of profits. The first order condition is: $[\pi(n;o) - \pi(o;o)] - a(k+r)e^{-kt_1} = 0$. Therefore the optimal adoption time is as followings: When $\frac{\pi(n;o) - \pi(o;o)}{a} < k + r$,

$$t_1^* = -\frac{1}{k} \ln\left[\frac{\pi(n;o) - \pi(o;o)}{a(k+r)}\right]; \tag{4.1}$$

when $\frac{\pi(n;o) - \pi(o;o)}{a} \geq k + r$,

$$t_1^* = 0. \tag{4.2}$$

It confirms that the optimal adoption time is independent of the other firm's imitation time, but depends on *ex post* the market structure. It also is decreasing in $[\pi(n;o) - \pi(o;o)]$ and increasing in a, r, k. An increase in sufficiently large profit, $[\pi(n;o) - \pi(o;o)]$; and a sufficiently small initial cost a; an interest rate r; and a marginal cost of adoption k stimulate the immediate purchase of the technology.

Now consider the optimal technology imitation time with our specific cost functions. Without loss of generality, let firm 1 be a domestic adopter for technology and then its problem is the following: Given t_2, technology adoption by firm 1 $\max_{s \in [0, \infty]} V_1(t_2 + s, t_2)$ where

$$V_1 = \int_{t_2}^{s+t_2} e^{-rt}[\pi(o;n) - \pi(o;o)]dt$$
$$+ \int_{s+t_2}^{\infty} e^{-rt}[\pi(n;n) - \pi(o;o)]dt - ae^{-[(k+r)t_2 + (h+r)s]}.$$

Clearly, the first order condition is: $[\pi(n;n) - \pi(o;o)] - a(h+r)e^{-(kt_2 + hs)} = 0$. Therefore the optimal imitation lag $s^*(t_2)$ is as followings: When $\frac{e^{kt}[\pi(n;n) - \pi(o;n)]}{a} < h + r$,

$$s^*(t_2) = -\frac{1}{h}\left[\ln\left[\frac{\pi(n;n) - \pi(o;n)}{a(h+r)}\right] + kt_2\right]; \tag{5.1}$$

when $\frac{e^{kt}[\pi(n;n)-\pi(o;n)]}{a} \geq h+r$,

$$s^*(t_2)=0. \tag{5.2}$$

It is worth noting properties of the optimal imitation lag. First, as in Lemma 2, the optimal imitation lag is a decreasing function of the adoption time, i.e., $\frac{ds^*(t)}{dt}<0$. That is, the imitation lag will be shortened when the adoption for a new technology is delayed; but the size of that reduction is less than the delay of the adoption. Second, the imitation will be hastened, the greater the $[\pi(n;n)-\pi(o;n)]$; the smaller the interest rate r; the smaller the degree of diffusion speed h.

We now pin down Nash timing equilibria. Using Equations (4.1) and (4.2) and Equations (5.1) and (5.2), the possible Nash timing equilibria can be shown to be as follows: When $\frac{\pi(n;o)-\pi(o;o)}{a} \geq k+r$, the optimal adoption time is $t^*=0$. On the other hand, given $t^*=0$, the optimal imitation lags are followings:

$$s^*(0)=-\frac{1}{h}\ln\left[\frac{\pi(n;n)-\pi(o;n)}{a(h+r)}\right] \text{ if } \frac{\pi(n;n)-\pi(o;n)}{a}<h+r.$$

$$s^*(0)=0 \text{ if } \frac{\pi(n;n)-\pi(o;n)}{a} \geq h+r.$$

When $\frac{\pi(n;o)-\pi(o;o)}{a}<k+r$, the optimal time for the technology adoption is $t^*\neq 0$. Furthermore, given $t=t^*$ the optimal imitation lags are followings:

$$s^*(t^*)=-\frac{1}{h}\ln\left[\frac{(\pi(n;n)-\pi(o;n))(k+r)}{(\pi(n;o)-\pi(o;o))(h+r)}\right] \text{ if}$$

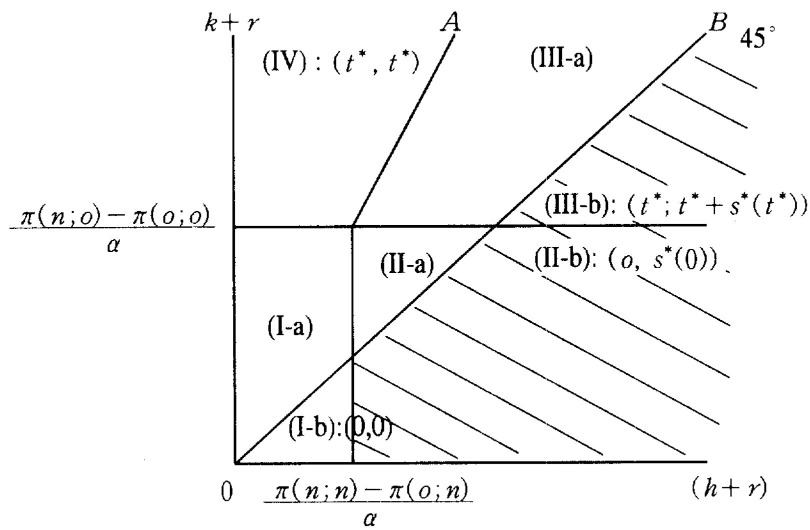
$$(k+r)<\frac{\pi(n;o)-\pi(o;o)}{\pi(n;n)-\pi(o;o)}(h+r).$$

$$s^*(t^*)=0 \text{ if } (k+r) \geq \frac{\pi(n;o)-\pi(o;o)}{\pi(n;n)-\pi(o;o)}(h+r).$$

We demonstrate the set of all Nash equilibria in Figure 3 for the relationship between the magnitude of k and h, and the possible realization of equilibria. (For diagrammatic simplicity we employed $(k+r)\times(h+r)$ space instead of $k\times h$ space.)

First, let us identify all regions in Figure 3. The conditions for Equations (4.1), (4.2), (5.1), and (5.2) determine the four regions. In Regions I-a and I-b, where both the cost reduction rate k and the domestic diffusion speed h are low, the adoption and the imitation will occur immediately, resulting in an equilibrium at (0, 0). In Regions II-a and II-b, where k is small and h is large, the adoption will occur immediately and the imitation will occur at some time later, resulting in a possible equilibrium at $(0, s^*(0))$. In Regions III-a and III-b,

[Figure 3] Nash Solutions with Values of k and h



where both k and h are large, the adoption will occur at some positive time t^*, and the imitation will occur at some later time, resulting in a possible equilibrium at $(t^*, t^*+s^*(t^*))$. Finally in Regions IV-a and IV-b, where k is large and h is small, the adoption will occur at t^*, and the imitation follows it immediately, resulting in a possible symmetric equilibrium at (t^*, t^*).

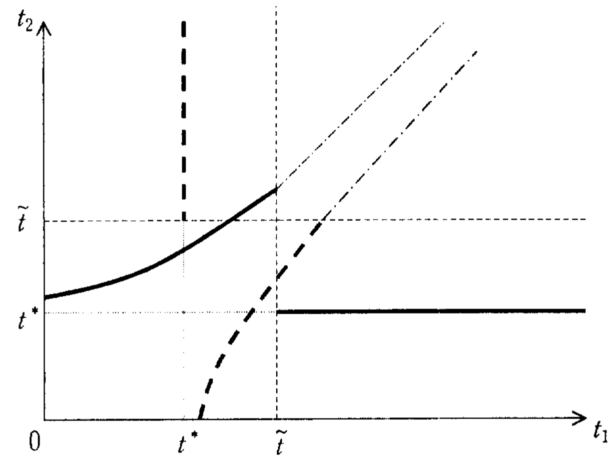
Second, the slope of OA-line is $\frac{\pi(n;o)-\pi(o;o)}{\pi(n;n)-\pi(o;n)}$ under the condition for $s^*(t^*)$. The condition that $h>k$ for both cost functions for technology adoption and imitation also determines that the slope of OB-line is 45°. Together with Assumption 4, OA-line lies above OB-line. Hence, only regions below OB-line are relevant and thus we confirm Lemma 3, i.e., the solutions in Region IV are excluded.

The Waiting Game Problem in Technology Dissemination

Recall that Proposition 1 assumes the existence of Nash Equilibria. In this subsection we will examine when equilibrium may not exist. This non-existence is identified as a waiting game problem, which realized in the literature (e.g., Katz and Shapiro (1992)). We find in this subsection that this waiting game problem for optimal timing decision is common in a model of technology dissemination.

This problem occurs when a firm moves first at time t and the other firm follows at time $t+s(t)$. Since $t+s(t)$ is less than $\tilde{t}$ − defined in Lemma 4, the first firm is better off to choose its imitation time, $[t+s(t)]+[s(t+(s))]$. Therefore no firm moves first, and thus there is no equilibrium in this game.

[Figure 4] Non-existence for a Nash Technology Dissemination Game



This waiting problem comes from an individual firm's unwillingness to adopt unilaterally; expectations about when the rival firm will follow are crucial to the behavior of the initial adopters.

Intuitively, the waiting game problem can arise if the domestic diffusion of the technology is too fast, resulting in an imitation lag that is too short. The shortened imitation lag will raise the follower's net profit and lower the leader's net profit. Even though the net benefit of the leading is positive, the net benefit of the following is greater than that of the leading so every firm would rather be a follower than a leader. That is, there will not be any leader; no firm can be a follower either. The figure below demonstrates such possibility.

Now we will demonstrate the waiting game problem in our model. Since we cannot explicitly compare the size of $\tilde{t}$ and $t^*+s^*(t^*)$ (because $\tilde{t}$ is not explicitly determined in Lemma 4), we will compare the change of $\tilde{t}$ and $s^*(t^*)$ with respect to the domestic diffusion speed h, to see the relationship between the size of h and equilibrium outcomes.

Recall that $\varDelta(t) \equiv V_1(t^*;t) - V_1(t+s^*(t);t)$ in Proof of Lemma 4. We may also recall that $\tilde{t}$ satisfies that $\varDelta(\tilde{t})=0$. Using the condition for optimal $s^*(t^*)$ for $t^* \geq 0$ under our specification of the cost functions, we have $\varDelta(t)$ as followings: When $k+r > \dfrac{\pi(n;o)-\pi(o;o)}{a}$,

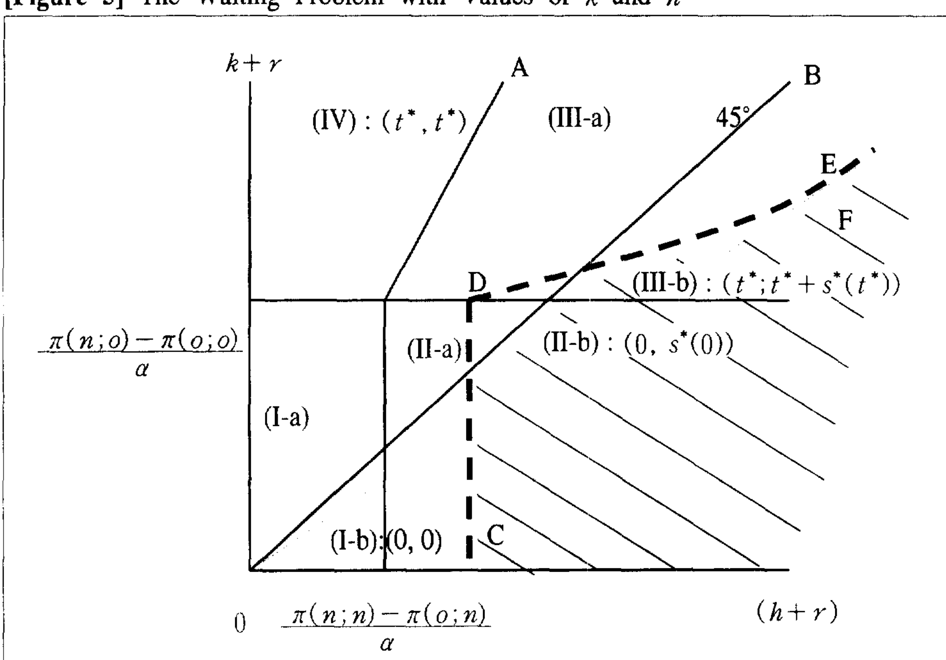
$$\varDelta(t) = ae^{-(k+r)t}[e^{-(h+r)s^*(t)}-1] + \int_{t^*}^{t} e^{-ru}[\pi(n;o)-\pi(o;o)]du + \int_{t}^{t+s^*(t)} e^{-ru}[\pi(n;n)-\pi(o;o)]du.$$

When $k+r \leq \dfrac{\pi(n;o)-\pi(o;o)}{a}$,

$$\Delta(t)=\alpha[e^{-(k+r)t-(h+r)s^*(t)}-1]+\int_0^t e^{-ru}[\pi(n;o)-\pi(o;o)]du$$
$$+\int_t^{t+s^*(t)} e^{-ru}[\pi(n;n)-\pi(o;o)]du.$$

First, consider Regions III-a and III-b in which $(t^*,\ s^*(t^*))$ is an equilibrium. The relation between s^* and h can be expressed as $\frac{\partial s^*(t^*)}{\partial h}=\frac{1}{h}\left[\frac{1}{h}\ln\left[\frac{\pi(n;n)-\pi(o;n)}{\pi(n;o)-\pi(o;o)}\frac{k+r}{h+r}\right]+\frac{1}{h+r}\right]$. Hence $\frac{\partial s^*(t^*)}{\partial h}\leq 0$ if and only if $k+r\leq\left[e^{-\frac{h}{h+r}}\right]\left[\frac{\pi(n;o)-\pi(o;o)}{\pi(n;n)-\pi(o;n)}\right][h+r]$. Furthermore, using the implicit function theorem for $\Delta(t)$ above, we have $\frac{d\tilde{t}}{dh}$ for all h under Assumption 4; the decreasing property of the optimal imitation lag, i.e., $\frac{ds^*(t)}{dt}<0$ (see the argument below Equation (5.2)).[16] Given the reference-curve, say DE-curve for $\frac{\partial s^*(t^*)}{\partial h}=0$ in Figure 5, which approaches to OF-line whose slope becomes $[e^{-1}]\left[\frac{\pi(n;o)-\pi(o;o)}{\pi(n;n)-\pi(o;n)}\right]$ as $h\to\infty$.[17] That is, all points below DE-curve has the property that $\frac{d\tilde{t}}{dh}>0$. Therefore, these points can suffer from the waiting game problem.

[Figure 5] The Waiting Problem with Values of k and h



[16] We apply Leibnitz's Rule for differentiating an integral with respect to a parameter, see for example Rudin (pp. 144, 1973).

[17] For illustration, we add a technical assumption in order to ensure DE-line intersects with OB-line: $e^{-1}[\pi(n;o)-\pi(o;o)]<\pi(n;n)-\pi(o;n)$. Otherwise, there is no solution at Region III-b.

Now, consider Region II. That is, $\frac{\partial s^*(t^*)}{\partial h} = \frac{1}{h}\left[\frac{1}{h}\ln\left[\frac{\pi(n;n)-\pi(o;n)}{\alpha(h+r)}\right] + \frac{1}{h+r}\right]$ when $t^*=0$. Therefore, $\frac{\partial s^*(t^*)}{\partial h} \leq 0$ at $t^*=0$ if and only if $h+r > \left[e^{\frac{h}{h+r}}\right]\left[\frac{\pi(n;n)-\pi(o;n)}{\alpha}\right]$. In particular, we define $\overline{h+r}$ where $\frac{\partial s^*(t^*)}{\partial h}=0$. This becomes $\frac{\pi(n;n)-\pi(o;n)}{\alpha} < \overline{h+r} < \frac{\pi_n(n;o)-\pi(o;o)}{\alpha}$. Hence, CD-line represents $\overline{h+r}$ and thus locates between OA-line and OB-line at $k+r=\frac{\pi(n;o)-\pi(o;o)}{\alpha}$ for the $(k+r)-$axis. Using the same method as the above case that $t^*\neq 0$, it is easy to show that $\frac{d\tilde{t}}{dh}>0$ whenever $\frac{\partial s^*(t^*)}{\partial h}\leq 0$. Hence, all points at the right area of CD-line also suffer from the waiting game problem. We then recognize that equilibrium strategies in technology dissemination game can occur on the Regions I-b; the part of Region II-b at the left of CD-line; and the part of Region III-b below OB-line and above DE-line.

In sum, all points below CDE-curve satisfy $\frac{d\tilde{t}}{dh}>0$ and bear the waiting game problem. That is, as $h+r$ increases, the imitation lag is shortened, whereas $\tilde{t}$ is increased. Therefore when the degree of the domestic diffusion speed h is high (relative to the rate of cost reduction for the international adoption k), the gap between $\tilde{t}$ and $t^*+s^*(t^*)$ should be wider. Hence, is suggests that the waiting game problem can be caused by a relatively high domestic diffusion speed.

Ⅳ. CONCLUDING REMARKS

We defined technology as the exclusive right to use a blueprint to produce a commodity in a certain limited market. Because of the single unit-demand characteristic of a technology, the decision to adopt a new technology is a timing problem, rather than a quantity problem. In our dynamic game-theoretical setting, we show Nash equilibria in models of technology dissemination. We also demonstrate possibility of non-existence of a solution in the waiting problem under a usual technology competition.

The basic model in this paper is general enough to provide many avenues for extending our analysis. We could introduce an international firm in the technology-adopting sector, so that we might investigate some interesting questions by including, for example, strategic behaviors between technology buyers and sellers, preemptive strategies, limitation and licensing, and uncertainties of innovation. We also could add a market for a manufacturing good produced with a new technology to endogenize a dynamic comparative advantage in international markets. It would enrich our analysis in the context of completing a final good market and its underlining technology. Finally, we could extend our framework to a model with network externalities as in Katz and Shapiro (1992). We will leave these interesting topics for future research.

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