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STRATEGIC TIMING OF TECHNOLOGY DISSEMINATION*

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Abstract: In a dynamic game-theoretical model, this paper investigates the open-loop equilibrium timing of international and domestic technology adoption and diffusion. By extending the model of innovation rivalry by Katz and Shapiro (1987) to one of dissemination of a new technology in the presence of heterogeneous sectors, this paper sheds light on the sequential decision processes in international and domestic markets. This paper demonstrates the interdependence of timing decisions, including a waiting equilibrium in the two markets, and evaluates the welfare effect of a new technology. Results in our model suggest policy recommendations at a micro- and macro-level of the economy.

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I. INTRODUCTION

Technological progress is considered a leading engine of long-run economic growth. The benefit of a new or improved product or production process accrues through its adoption or dissemination[1] to the society until it is supplanted. This paper examines the effect of technology adoption or dissemination when the innovation has been perfected in a dynamic game-theoretical model. In particular,

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[1] Intentionally and abusively, we use 'adoption' and 'dissemination' synonymously. It is because we consider that a new technology is tradable as well as has an externality effect. We hope that it becomes clear for readers when we set up the model.

we analyze the extent and timing of technology adoption when buying and selling of perfected innovation is determined strategically in the international and domestic market.

Dissemination of a new technology appears to be a slow and incremental process (Rosenberg and Birdzell (1986); Mokyr (1990)). Stenbacka and Tombak (1994), Hindricks (1992), and Jensen (1992) attribute this to market uncertainties. Farzin et al. (1998) and Purvis et al. (1995) examine irreversibility with technological shocks as a source of the slow adoption of a new technology. Kamien and Schwartz (1972) and Katz and Shapiro (1987) find that in the rivalry of innovation, adoption and imitation affect the timing and potential reward of technology.[2] By extending the results of the dissemination effect of innovation in Katz and Shapiro (1987) to ones in the adoption of a new technology in the presence of heterogeneous sectors, this paper sheds light on the sequential decision processes in international and domestic markets. We focus on strategic behaviors between the provider and adopter of technology and investigate the impact of heterogeneous sectors on technological diffusion in the overall economy.

For this purpose we set up an economy consisting of many sectors: a sector in which a firm directly adopts a new technology from the foreign country; and other sectors in which firms enjoy knowledge spillover from domestically available technology because of a sector-wide learning economy. In this simple model of technology dissemination, we examine both the strategic behavior of technology adoption from a foreign economy and its diffusion effects on sectors of the domestic economy.

The closest work to ours is the insightful paper by Katz and Shapiro (1987), 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 several aspects: (1) Rather than analyzing R&D competition, it emphasizes a two-person game at the market for technology adoption, specifying a provider and a buyer of a perfected technology; (2) There are heterogeneous sectors in the technology adopting economy and this paper thereby is concerned with the timing of adoption in the presence of beneficiary sectors for a newly-arrived technology in its own economy; (3) It generalizes a usual cost function of adoption in the literature by assuming the function to be a function of both the timing of international adoption and domestic dissemination; (4) It examines the change in the value of a new technology and thus the welfare of the society; and (5) It addresses policy implications when a government interferes in the technology adopting sector in order to correct some market failure due to the public good nature of the technology.

This paper presupposes that the mechanism for international technology adoption

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[2] For survey on the subject, the reader shell be referred to Reinganum (1989) and Bridges et al. (1991).

is different from the one for domestic diffusion. 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 adoption in the international market is likely to require a means of licensing or transfer, which often involves a strategic behavior between a provider and an adopter of technology.[3] Following Reinganum (1981), Fudenberg and Tirole (1985), we are concerned with the game-theoretical analysis on the nature of international technology dissemination. 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. Lee (1984) and Stenbacka and Tombak (1994) extend our model to an economy where there are two potential buyers for a new technology from a foreign market. However, contrary to their model, we focus on strategic timing decisions at the international technology trade and then investigate the effect of their interdependence of the provider and buyer of technology. We also analyze the effect of their interdependence when an open economy simultaneously experiences both international and domestic dissemination.

Once a new technology is adopted in a sector of the economy, the other sectors will benefit from the newly available technology and domestic dissemination will take place, this is the nature of public-good technology.[4] This paper studies this diffusion effect on the timing of domestic technology adoption in the other sectors of the economy: How the timing of domestic adoption is affected by the timing of international adoption. Our model also allows us to describe the interdependence of the sectoral and aggregate effects of technology dissemination and thus it can be used to make normative policy recommendations.

That is, the results of this paper provide interesting policy implications. When there are positive externalities of international technology adoption in the economy, the government can choose industrial policies to improve the welfare of the economy. We consider two policy instruments: direct timing control of international technology adoption and price control to stimulate a firm to choose a Pareto improved timing of international adoption. We show that the socially desirable timing of adoption should be earlier than the equilibrium timing of international adoption, and that the interest-setting policy must lower interest rates in the sector that would adopt a new technology from outside the economy.

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[3] Empirical findings show asymmetry between domestic and foreign technology dissemination. Stenbacka *et al.* (1994) reports that firms tended to issue licenses twice as often to domestic firms as to foreign firms during the period 1975-80. Kindelberger (1995) also surveys European experiences in technology diffusion among countries.

[4] In our model, we assume that spillover of a newly adopted technology exists in the domestic market but no spillover of a newly arrived technology in the international market. As mentioned in footnote 3, this assumption is not very restrictive as long as the speed of disseminations are asymmetric and international diffusion is slower than domestic diffusion. Also refer to interpretation for the obsolete function G(t) of the new technology in Section 2.

However, we may note that Ridordan (1992) shows otherwise when a firm can play preemptive strategies.

This paper processes as follows. Section 2 builds a dynamic model of international technology adoption. Equilibrium in a game-theoretical decision-making model with a convex price mechanism is analyzed in Section 3. Section 4 introduces many heterogeneous sectors and determines the domestic adoption timing of a newly available technology in the economy. This section also examines the effects of international technology adoption on the timing of domestic dissemination and on the value of a firm and thus the welfare of the economy. Section 5 considers government policies for welfare improvement in presence of positive effects of technology adoption. Concluding remarks are in Section 6.

Ⅱ. THE BASIC MODEL

We consider a technology to be a set of ideas embodied in a blueprint which renders a stream of future services in the form of profits. As long as one owns the blueprint that can be used exclusively for production process, the stream of profits depends on the demand in a certain market for the products produced using that blueprint. That is, ownership of the blueprint is the exclusive right of using the corresponding technology of which the use is restricted to the production of final products to be sold in the market. Thus, adoption of a new technology can occur for a firm seeking profit by producing the final good.

We differentiate a foreign market in Country 1 from a domestic market in Country 2 in order to study technology dissemination both between countries and between sectors in the domestic economy of Country 2. The firm in Country 1 has the new technology and may sell this technology to Country 2. The firm in Country 2, which does not have the new technology, is the only prospective buyer of the technology.[5] From now on we will call Country 1 the selling country, and Country 2 the buying country. In this study our interest will be restricted to technology, i.e., the exclusive right to use the technology in the market of the buying country. We then assume that the final products are tradable between two counties. We also assume that the two countries differ only in wage levels; the wage level, w_1 in Country 1 is higher than that of Country 2, w_2 i.e., $w_1 > w_2$.[6]

[5] Lee (1984) extends to the case that many potentially buying firms in Country 2 strategically decide when they adopt a new technology from an international market. He shows that this waiting game may have no equilibrium. However, his model is simpler than the present model in the sense that there is no strategic behavior between a seller and a buyer for a new technology.

[6] Actually, this wage differential is representative of the comparative advantage of the buying country with respect to the selling country. Other comparative advantages arise from, for example, relatively smaller stock of old-vintage capital equipment which should be replaced by the new technology.

The demand for the final products is assumed to be stationary over time in the buying country. Therefore, the selling firm expects to receive a profit flow π_1 per period not by selling the technology, but by using it to produce goods for export to the buying country. This type of profit function subsequent to its own technology is widely used in the literature (for example, see Katz and Shapiro (1987)). The profit is assumed to be a function of an input price, the cost of labor. Hence, $\pi_1 = \pi(w_1)$. This specification allows us to study the impact of comparative advantage on technology adoption in the later sections. We then assume that π decreases in w. Similarly the buying firm in Country 2 expects to get a profit flow $\pi_2 = \pi(w_2)$ per period, by using the technology to produce products in its own country to meet its country's market demand. Notice that $\pi_2 - \pi_1 > 0$ since we assume that that π decreases in w.

Mimicking the expenditure function for R&D in Kamien and Schwartz (1972) and many others in the R&D literature, we assume that the cost of adoption is a function of time. This cost is a one-shot sunk cost and will be borne by the buying firm at time t.[7] The adoption cost function $c(t)$ is also assumed to be decreasing at a declining rate, i.e., $c'(t)<0$, $c''(t)\geq 0$.[8] Together with the assumption of the profit function that $\pi'(w)\leq 0$ this assumption of the cost function ensures the existence of adoption equilibrium. The above assumptions are equivalent to those in Quirmbach (1986) and Fudenberg and Tirole (1985).

The technology will become obsolete when there is a more advanced technology which supersedes the existing technology. The probability that the existing technology will become obsolete by time t is $G(t)$.[9] That is, $G(t)$ is an existing firm's cumulative distribution over an arrival time t of a new technology. Thus, the density function associated with the cumulative function is $G'(t)$. Therefore, $G'(t\,|\,\hat{t}) = G'(t)[1-G'(\hat{t})]^{-1}$ is the probability that the technology will become obsolete at time t given that it has not yet become obsolete by the time $\hat{t}$. The selling firm will sell the technology only if the price of the technology is higher than the expected discounted future profits from the exports of its products to the buying country. So the selling reservation price of the technology for the selling firm at time $\hat{t}$ is at given the interest rate r,

$$R_1(\hat{t}) = [1-G(\hat{t})]\int_{\hat{t}}^{\infty} G'(\bar{t}\,\big|\,\hat{t})\Big\{\int_{\hat{t}}^{\bar{t}} e^{-rt}\pi_1 dt\Big\}dt. \tag{1}$$

[7] The assumption about who bears the cost is not essential in our model. The time of transfer is not affected, only the income distribution between the buyer and the seller is affected.

[8] The technology adoption cost is specific to the technology and the countries involved. The larger the gap between the selling country and the buying country in general science and technological bases, the higher the transfer cost (see Teece (1976) for details).

[9] Here we assume that $G(t)$ is a differential function and $G'(t)$ denotes its derivative.

Similarly, the buying firm will buy the technology only if the price of the technology is lower than the expected net discounted future profits from the technology. So the buying reservation price of the technology is:

$$R_2(\hat{t}) = [1 - G(\hat{t})]\left\{ \int_{\hat{t}}^{\infty} G'(\bar{t}\,|\,\hat{t})\left(\int_{\hat{t}}^{\bar{t}} e^{-rt}\pi_2 dt \right) d\bar{t} - e^{-r\hat{t}} c(\hat{t}) \right\}. \quad (2)$$

The technology transfer can take place if $R_2(\hat{t}) > R_1(\hat{t})$ for some $\hat{t} \in [0, \infty)$.

Now, suppose that the market price of the technology $P(\hat{t})$ at the time $\hat{t}$ is $P(\hat{t}) \in [R_1(\hat{t}), R_2(\hat{t})]$, We define that $V_i(t)$, $i = 1, 2$, is the value of international technology transfer for Country i at time t. Then, the problem for selling firm's in Country 1 is summarized as $\underset{\hat{t}}{Max}\ V_1(\hat{t}) = P(\hat{t}) - R_1(\hat{t})$, and the buying firm's problem in Country 2 as $\underset{\hat{t}}{Max}\ V_2(\hat{t}) = R_2(\hat{t}) - P(\hat{t})$.[10] Therefore, each firm makes its timing decision based on the present value criterion. We assume that their decisions should not be revised, so thereby the solution to optimization problems becomes an open-loop equilibrium.

We define a convex-combination pricing rule as $P(\hat{t}) = \sigma R_1(\hat{t}) + (1-\sigma) R_2(\hat{t})$, $\sigma \in [0, 1]$. This convex-combination pricing rule in a zero-sum game is general enough to include the Stakleberg solution and the Nash Bargaining solution as special cases.[11] When $\sigma = 0 (\sigma = 1)$ the price rule represents the selling firm's (the buying firm's) Stakleberg leadership. Furthermore when $\sigma = 1/2$, this price rule represents the Nash bargaining solution. In general, σ captures the degree of the bargaining power of the selling firm, while $1 - \sigma$ represents the degree of bargaining power of the buying firm. A timing problem of technology adoption with a monopolistic supplier is also introduced in Katz and Shapiro (1992) and this paper generalizes their model by considering a strategic behavior for a decision against the buyer of technology.

Suppose $V(\hat{t}) = R_2(\hat{t}) - R_1(\hat{t})$. We now describes the technology adoption game as:

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[10] However, reversibility in the investment theory complicates the present value criterion, and we thus presuppose that the adoption of technology is irreversible. Farzin *et al.* (1998) study timing of adoption of a new technology under the irreversibility assumption, but they are more interested in how the level of technology efficiency is determined under technological uncertainty.

[11] Here, we can explicitly setup a game between two countries. Because of a linear payoff function, this game becomes a zero-sum game. Particularly, in a Nash game, each chooses its optimal price given a price chosen by the other as long as the other maintains non-negative profit. Therefore each player's reaction function is in $[R_1(\hat{t}), R_2(\hat{t})]$. Hence, a Nash solution is one in which the both share the same profit from the value of the capital. On the other hand, in a Stakleberg game, since the leader can override the follower action, a solution is one in which the leader chooses the price, in which the leader gets all potential profit and the follower maintains at zero profit.

Lemma 1 : *If the price of the technology is determined by the convex-combination pricing rule, then the buyer's problem and the seller's problem become equivalent, i.e.,*

$$\arg \underset{\hat{t}}{Max}\ V(\hat{t}) = \arg \underset{\hat{t}}{Max}\ V_1(\hat{t}) = \arg \underset{\hat{t}}{Max}\ V_2(\hat{t}).$$

Proof : Recall $V_1(\hat{t}) = P(\hat{t}) - R_1(\hat{t})$ Then, $V_1(\hat{t}) = (1-\sigma)[R_2(\hat{t}) - R_1(\hat{t})]$. Similarly, $V_2(\hat{t}) = \sigma[R_2(\hat{t}) - R_1(\hat{t})]$. Then, $V_1(\hat{t}) = (1-\sigma)V(\hat{t}) = \frac{(1-\sigma)}{\sigma} V_2(\hat{t})$ and thereby the lemma holds.

Lemma 1 implies that the relative position of bargaining power in the game assigns the share of gains of the technology trade but does not affect the timing of technology adoption under the convex-combination price rule. This convex-combination price rule also simplifies the timing decision for the players either in a Nash or Stakleberg game.

Ⅲ. CHARACTERISTICS OF INTERNATIONAL TECHNOLOGY ADOPTION

In this section we determine the conditions for equilibrium timing for international technology adoption including the case of staying with the old technology. By using Equations (1) and (2), Lemma 1 implies that the technology selling firm's and the buying firm's optimization problems become

$$\underset{\hat{t}}{Max}\ V(\hat{t}) = [1 - G(\hat{t})]\left\{\int_{\hat{t}}^{\infty} G'(\bar{t}\,|\,\hat{t})\left[\int_{\hat{t}}^{\infty} e^{-rt}[\pi_2 - \pi_1]dt\right]d\bar{t} - e^{-rt}c(\hat{t})\right\}. \quad (3)$$

Hence, $V(\hat{t})$ represents the expected discounted value of the total surplus arising from the technology adoption at time $\hat{t}$.

Now, we assume that the arrival of more advanced technology is a Poisson process, so the probability of the obsolescence of the technology, $G(t)$ is exponentially distributed over time:

$$G(t) = 1 - e^{-\lambda t} \quad (4)$$

with $G(0) = 0$ and $\lim_{t \to \infty} G(t) = 1$.[12] As in Kamien and Schwartz (1972), and Stenbacka and Tombak (1994), the constant λ is a 'hazard rate' that the new technology will be introduced in the next instant of time after time t. Clearly, a

[12] Here, we can combine an international rate of spillover, if exists and exogenous, with the obsolete function, $G(t)$, of the new technology, i.e., $G(t) = 1 - e^{-(\lambda + \upsilon)t}$ where υ is a rate of international technology diffusion. Clearly, this specification of $G(t)$ would not alter main results in the paper.

higher λ represents faster technology change, which is assumed to be exogenous and is rationally expected with certainty by both players (see models of uncertainty of innovation, e.g., Farzin *et al.* (1998)).

Now we can obtain the following results about the determination of technology adoption time through the seller's and the buyer's optimization in the international markets. The next proposition derives the condition on the timing of international adoption. It also reports the two critical values: one in where the international adoption takes place immediately; the other in which the adoption never takes place. The latter is a waiting game exactly as realized in the literature (e.g., Katz and Shapiro (1992)), which can occur at strategic behaviors providing the condition in Case Ⅲ.

Proposition 1: *The open-loop equilibrium time t^* of the international technology adoption taking place is determined as follows:*

Case Ⅰ: $t^*=0$ when $V(0)>0$ and $\pi_2-\pi_1>(\lambda+r)c(0)-c'(0)$;
Case Ⅱ: $t^*=\hat{t}$ such that

$$\pi_2-\pi_1=(\lambda+r)c(\hat{t})-c'(\hat{t}) \tag{5}$$

when $V(t)>0$ for some $t\in(0,\infty)$, and $\lim_{t\to\infty}[(\lambda+r)c(t)-c'(t)]<\pi_2-\pi_1<(\lambda+r)c(0)-c'(0)$;

Case Ⅲ: $t^*=\infty$ when $V(\hat{t})<0$ for all $t\in(0,\infty)$, or $\pi_2-\pi_1<\lim_{t\to\infty}[(\lambda+r)c(t)-c'(t)]$.

Proof: Substituting Equation (4) into Equation (3), and rearranging it gives

$$V(\hat{t})=e^{-(\lambda+r)\hat{t}}\left\{\frac{\pi_2-\pi_1}{\lambda+r}-c(\hat{t})\right\} \tag{6}$$

Differentiating Equation (6) with respect to $\hat{t}$, we have

$$V'(\hat{t})=e^{-(\lambda+r)\hat{t}}\{-[\pi_2-\pi_1]+[(\lambda+r)c(\hat{t})-c'(\hat{t})]\}. \tag{7}$$

It is easy to check the second order condition for optimization. That is, by the negative monotonicity and the convexity of the adoption cost function,

$$V''(\hat{t})=e^{-(\lambda+r)\hat{t}}\{(\lambda+r)c'(\hat{t})-c''(\hat{t})\}<0.$$

If $V(\hat{t})<0$ for all nonnegative $\hat{t}$, then the transfer will not take place. If $\pi_2-\pi_1>(\lambda+r)c(0)-c'(0)$ and $v(0)>0$, then the transfer will take place immediately. If $\pi_2 - \pi_1 < \lim_{t \to \infty}[(\lambda + r)c(t) - c'(t)]$, then the firms will delay the transfer indefinitely.

By Equation (7), the interior solution for the private optimal time of technology transfer is given by $t^* = \hat{t}$,

$$\pi_2 - \pi_1 = (\lambda + r)c(t^*) - c'(t^*). \tag{8}$$

Therefore the proposition follows. □

The condition (8) is analogous to Equation 3 in Katz and Shapiro (1987). The LHS of Equation (8) $\pi_2 - \pi_1$,[13] represents the forgone profit due to the delay of the international adoption by one period, and the RHS of (8) represents the sum of the saved service flow of the adoption cost $c'(t)$ and the cost reduction $(\lambda + r)c(t)$ due to waiting one more period. Related to capital investment theory, the first term on the RHS also corresponds to the capital gain of not spending earlier. At the equilibrium 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.

On the other hand, immediate adoption happens when this value is strictly positive and the forgone benefit of the delay is exceeded by the cost saving of delay of the adoption in case I. In Case III, the adoption never takes place either when its value never becomes positive or the forgone profit stays lower than the cost saving of waiting for adoption.

Before adopting a new technology, a firm is naturally concerned about uncertainties regarding future technological progress. As in Kamien and Schwartz (1972), the following Lemma predicts that the international adoption slows down when a new technology arrives at a faster speed. However, this result is in contrast to one in models of strategic behavior involving more than one technology adopter (for details, see Stenbacka and Tombak (1994), Reinganum (1981) and Fudenberg and Tirole (1985)). Formally,

Corollary 1: *Assuming an interior solution as in Case II, Proposition 1, the faster (slower) rate of progress on a new technology delays (hastens) technology adoption in the international market.*

Proof: Recall that λ represents the speed of exogenous technical change in Country 1. Thus we need to show that $\frac{\partial t^*}{\partial \lambda} > 0$. Applying the implicit function theorem to Equation (5), we get $\frac{\partial t^*}{\partial \lambda} = \frac{-c(t^*)}{[(\lambda + r)c'(t^*) - c''(t^*)]}$ where t^* is a solution for international adoption. The second order condition ensures that

[13] In our model $(\pi_2 - \pi_1)$ can be interpreted as an adoption incentive. Similarly, Katz and Shapiro (1987) refer to $(\pi_2 - \pi_1)$ as a stand-alone incentive in the context of dynamics R&D competition.

$\frac{\partial t^*}{\partial \lambda} > 0$. □

It is intuitive that the value of adopted technology transforming into the value of the firm decreases when a new technology is introduced at a faster rate. Formally,

Corollary 2: *Assuming an interior solution in Case II, Proposition 1, the faster (slower) rate of progress on a new technology decreases the resulting value to the firm.*

Proof: Suppose that $V^* \equiv V(t^*(\lambda))$ from Equation (6). By using the envelope theorem we have

$$\frac{dV^*}{d\lambda} = \frac{dV(t^*(\lambda);\lambda)}{d\lambda} = \frac{\partial V(t^*,\lambda)}{\partial \lambda} = e^{-(\lambda+r)t^*}\left\{(-t^*)\left[\frac{\pi}{\lambda r} - c(t^*)\right] - \frac{\pi}{(\lambda+r)^2}\right\} < 0,$$

where $\pi \equiv \pi_2 - \pi_1$. By Case II, Proposition 1 $V(t^*) = \frac{\pi}{\lambda + r} - c(t^*) > 0$ at the interior solution and thereby the above inequality holds. □

Now, we consider the effect of the cost of adoption on the timing of technology adoption in the international market. Without loss of generality we may specify the adoption cost function as an inverse function of the timing of adoption: $c(t) \equiv \frac{k}{t}$ where $k > 0$. Clearly, this function satisfies two properties of the adoption cost function in our model: monotonic increase and convexity in t.[14] With this specification of the cost function, the higher k increases the ex ante cost of adoption at any time t. Then we establish that the relation between the timing of international adoption and its cost:

Corollary 3: *Suppose that the firm in Country 2 adopts a new technology at the strictly positive finite time. The higher (lower) adoption cost delays (hastens) technology transfer.*

Proof: It is sufficient and easy to show that $\frac{\partial t^*}{\partial k} > 0$ by comparative static analysis by the same method as in Corollary 1. □

Jensen (1982) finds the same result in a model of decision theory. Empirical works, for example in Teece (1976), support this result. He compares transfer

[14] Alternative specification of the adoption function can be used without altering main results in the paper. For example, $c(t) \equiv ke^{-at}$, $k>0$; $a>0$. We can carry out the same exercise by increasing k.

times for different countries and reported that the adoption cost is positively related to the dissemination time. However, it is worthwhile to note that this result may not be robust when we treat the cost as a flow over time as in an R&D model of Lee and Wilde (1980).

In international trade literature, comparative advantage becomes critical to determining a dynamic pattern of trade over time (see Grossman and Helpman (1991)). It is clear that an input market for production affects demand for a new technology. Our casual observation shows that demand for a new technology is stimulated when the cost of inputs increases in a country. We examine how the cost of inputs for production affects the timing of technology adoption: Recall that the wage differential, i.e., $(w_1 - w_2)$, is representative of the comparative advantage of the buying country with respect to the selling country in this one input-factor production mode. Lemma 2 establishes that input cost differences in production affect the timing of technology adoption. Lemma 3 shows that the value of each firm increases with wage differences.

Lemma 2: *The higher (lower) the wage differential between the selling country and the buying country leads to the earlier (later) international technology adoption.*

Proof: To show that $\frac{\partial t^*}{\partial(w_1 - w_2)} < 0$ it suffices that $\frac{\partial t^*}{\partial w_1} < 0$ and $\frac{\partial t^*}{\partial w_2} > 0$

By Equation (5), $\frac{\partial t^*}{\partial w_1} = -\frac{(\lambda + r)c'(t) - c''(t)}{\pi'(w_1)} < 0$, since the numerator is negative by the second order condition and the assumption $\pi'(w_1) < 0$. Using the same method, we have that $\frac{\partial t^*}{\partial w_2} > 0$. □

Lemma 3: *The higher (lower) the wage differential between the selling country and the buying country implies the larger (smaller) benefit to both firms in technology trade.*

Proof: By using the same method of the proof in Corollary 2, Equation (6) implies that $\frac{\partial V(t^*)}{\partial w_1} = e^{-(\lambda + r)t} \frac{-\pi'(w_1)}{\lambda + r} > 0$; $\frac{\partial V(t^*)}{\partial w_2} = e^{-(\lambda + r)t} \frac{\pi'(w_2)}{\lambda + r} < 0$.

They imply that $\frac{\partial V^*}{\partial(w_1 - w_2)} > 0$. □

Even if we extend our model to include fixed capital equipment as another input-factor of production (see Kamien and Schwartz (1972)), the above results will hold. These results explain, at least partially, this casual observation: some underdeveloped countries adopt very recent advanced technologies earlier than some more advanced countries.

IV. EFFECTS ON TIMING OF INTERNATIONAL ADOPTION WITH DOMESTIC ADOPTION

In this section we consider the effects of domestic dissemination arising from the purchasing of a new technology on the international market. That is, many firms in many sectors (or industries) will take advantage of a newly introduced technology by applying it to their own production. For convenience, we divide the economy in buying Country 2 into two groups: Sector A and the other sectors, called Sector B. Let Sector A be the international technology adopting sector as in the previous sections; and Sector B be the rest of the sectors that engage in domestic dissemination after a new technology is adopted by Sector A. We continuously assume that there is a single firm in each Sector A, but that there are many firms in Sector B in Country 2. For simplicity, we assume that each firm is identical in Sector B.

For a representative firm in Sector B, the amount of external benefit $\pi_a = \pi_a(w_2)$ from domestic dissemination is assumed to be stationary over time. We define the domestic adoption cost as $d(t_a;\, t)$, where t_a is the domestic adoption time in Sector B given the international adoption time t from selling Country 1 as in previous sections. This adoption cost function generalizes the constant cost of adoption in Katz and Shapiro (1987). The domestic adoption cost is assumed to be decreasing in its own domestic adoption time and to be increasing in international adoption time. Formally, $\frac{\partial d(t_a;\, t)}{\partial t_a} < 0$; and $\frac{\partial d(t_a;\, t)}{\partial t} > 0$. Both assumptions are intuitive: The former means that a firm in Sector B can easily adopt an existing technology within, rather than at the outside of, its own economy. This is conceivable due to knowledge spillover among sectors in the same economy. The latter implies that the anticipated domestic adoption cost increases when the arrival of a new technology in its own economy is delayed. In sum, shortening the lag between international and domestic adoption incurs a higher cost of the adoption.

To ensure the existence of a solution for optimization we further assume that the cost function is concave in t_a, i.e., $\frac{\partial^2 d(t_a;\, t)}{\partial t_a^2} \geq 0$.[15] Furthermore, we add the technical assumption that $\frac{\partial^2 d(t_a;\, t)}{\partial t \partial t_a} \leq 0$. The role of this assumption will be discussed below. For example, $d(t_a;\, t) \equiv e^{-ht_a + kt}$, for $h, k > 0$ holds the above assumptions for the adoption cost function.

Suppose that the value of adoption for a firm in Sector B is $E(t_a;\, t)$. Then, the representative firm in Sector B solves the following problem: Given optimal international adoption time t^*,[16]

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

[16] Here, the argument is valid for any t taken by the firm in Sector A in Country 2, yet for

$$\begin{aligned}\underset{t_a}{Max}\ E(t_a;\, t^*) &= e^{-\lambda t_a}\left\{\int_{t_a}^{\infty}\lambda e^{-\lambda(\bar{t}-t)}\left[\int_{t_a}^{\bar{t}} e^{-rt}\pi_a dt\right]d\bar{t}\right\} - e^{-(\lambda+r)t_a} d(t_a;\, t^*)\\ &= e^{-(\lambda+r)t_a}\left\{\frac{\pi_a}{\lambda+r} - d(t_a;\, t^*)\right\}.\end{aligned}$$

The first order condition with respect to t_a is given by,

$$\frac{\partial E(t_a;\, t^*)}{\partial t_a} = e^{-(\lambda+r)t_a}\left\{-\pi_a + \left[(\lambda+r)d(t_a;\, t^*) - \frac{\partial d(t_a;\, t^*)}{\partial t_a}\right]\right\} = 0$$

The second order condition for the above problem is also satisfied under the second derivative properties of $d(t_a;\, t)$. Hence, we already obtain:

Proposition 2: *Given the purchase time t^* by the buying sector the open-loop equilibrium timing of domestic adoption t_a^* in Country 2 is as follows:*

Case I: $t_a^*(t^*) = t^*$ when $E(t_a^*,\, t^*) \geq 0$ and $\pi_a \geq (\lambda+r)d(t_a^*,\, t^*) - \dfrac{\partial d(t_a^*,\, t^*)}{\partial t_a}$, for $t_a^* = t^*$;

Case II: $t_a^*(t^*) \in (t^*,\, \infty)$ *such that*

$$\pi_a = (\lambda+r)d(t_a^*;\, t^*) - \frac{\partial d(t_a^*,\, t^*)}{\partial t_a}, \tag{9}$$

when $E(t_a,\, t^*) \geq 0$ for some $t_a \in (t^*,\, \infty)$ and $\lim\limits_{t^*\to\infty}\left[(\lambda+r)d(t_a;\, t^*) - \dfrac{\partial d(t_a;\, t^*)}{\partial t_a}\right] < \pi_a < (\lambda+r)d(t_a;\, t^*) - \dfrac{\partial d(t_a;\, t^*)}{\partial t_a}$.

Case III: $t_a^*(t^*) = \infty$ if $E(t_a,\, t^*) < 0$ for all $t_a \in [t^*,\, \infty)$, or $\pi_a \leq \lim\limits_{t_a\to\infty}\left[(\lambda+r)d(t_a;\, t^*) - \dfrac{\partial d(t_a,\, t^*)}{\partial t_a}\right]$.

Case I indicates that the benefit of domestic adoption 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. On the other hand, domestic dissemination would not happen when the sum of those costs is never recovered by the benefit of the adoption.

Let us characterize the equilibrium timing of domestic adoption. First, as long as domestic adoption occurs at a strictly positive finite time, we can find the resulting benefit of technology adoption. That is, we can define the value

convenience we assume that an optimal timing for international adoption is given.

function is $E^*(t^*) \equiv E(t_a^*(t^*); t^*)$:[17]

$$E^*(t^*) = e^{-(\lambda+r)t_a^*(t^*)}\left\{\frac{\pi_a}{\lambda+r} - d(t_a^*(t^*); t^*)\right\}. \tag{10}$$

Note that the value function represents the value of the new capital from the international market at time t^* — which includes benefits from domestic spillovers as well as international adoption — when domestic timing is optimally chosen. Second, we know that domestic adoption is delayed when a new technology arrives at a fast speed by showing $\frac{\partial t_a^*}{\partial \lambda} > 0$ in Equation (9). This result is parallel to the case of international dissemination in the previous section. Third, we want to examine how the timing and the value of domestic adoption in Sector B are affected by the timing of international adoption in Sector A of Country 2. Then, we have the following:

Corollary 4: *At the interior equilibrium domestic adoption time t^* in Case II, Proposition 2, the delay in international technology adoption also delays domestic adoption.*

Proof: From Equation (9), and using the implicit function theorem,

$$\frac{dt_a^*}{dt^*} = -\left[(\lambda+r)\frac{\partial d(t_a^*; t^*)}{\partial t^*} - \frac{\partial^2 d(t_a^*; t^*)}{\partial t^* \partial t_a^*}\right] \left[(\lambda+r)\frac{\partial d(t_a^*; t^*)}{\partial t_a} - \frac{\partial^2 d(t_a^*; t^*)}{\partial t_a^2}\right]^{-1} > 0. \tag{11}$$

The inequality holds since the first term of the RHS is positive by assumption of $d(t_a; t)$ and the second term of the RHS is negative by assumption of $d(t_a^*; t^*)$.[18] □

Now, we show that the value of a representative firm in Sector B is adversely affected by a delay in international adoption of a new technology:

Corollary 5: *At the interior equilibrium domestic adoption timing in Case II, Proposition 2, the delay of international technology adoption lowers the resulting value of domestic adoption.*

Proof: By Equation (10) and the assumption $\frac{\partial d(t_a; t)}{\partial t} > 0$ it is easy to check:

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[17] Clearly, Assumptions on $d(t_a; t)$ ensures existence of the value function by applying the implicit function theorem.

[18] We may note that the assumption that $\frac{\partial^2 d(t_a; t)}{\partial t \partial t_a} \leq 0$ is not fully used for the proof of the corollary. In fact, the corollary still holds when $\frac{\partial^2 d(t_a; t)}{\partial t \partial t_a} = 0$.

$$\frac{\partial E^*(t^*)}{dt^*} = e^{-(\lambda+r)t_a^*}\frac{dt_a^*}{dt^*}\left\{-\pi_a + \left[(\lambda+r)d(t_a^*;t^*) - \frac{\partial d(t_a^*;t^*)}{\partial t_a^*}\right]\right\} \tag{12}$$

$$-e^{-(\lambda+r)t_a^*}\frac{\partial d(t_a^*;t^*)}{\partial t^*} = -e^{-(\lambda+r)t_a^*}\frac{\partial d(t_a^*;t^*)}{\partial t^*} < 0.^{19} \quad \square$$

We investigate under what condition the adoption lag elapses between international and domestic adoption. A similar question has been asked by Fudenberg and Tirole (1985) and Stenbacka and Tombak (1994). The elapsed time between international and domestic technology adoption depends on – in addition to the interest rate and the arrival rate of a new technology – the joint effect of the net of changes in adoption costs and the net of the rates of changes in their costs. In particular, the first and second degree effects, $\left\|\left[(\lambda+r)\frac{\partial d(t_a^*;t^*)}{\partial t^*} - \frac{\partial^2 d(t_a^*;t^*)}{\partial t^*\partial t_a^*}\right]\right\|$, of international diffusion on the domestic adoption cost should be smaller than the first and second effects, $\left\|\left[(\lambda+r)\frac{\partial d(t_a^*;t^*)}{\partial t_a} - \frac{\partial^2 d(t_a^*;t^*)}{\partial t_a^2}\right]\right\|$, of domestic adoption to reduce the delay of domestic adoption after international transfer. Contrary to our result their conclusion depends on the roles of leaders and followers in technology adoption. The lemma below summarizes the conditions:

Corllary 6: *At the interior equilibrium domestic adoption time in Case II, Proposition 2, and under that condition that* $\frac{\partial^2 d(t_a;t)}{\partial t_a^2} > 0$,[20] *the delay in the time of international technology adoption reduces the elapsed time between interna tional and domestic technology adoption if and only if* $\left\|\left[(\lambda+r)\frac{\partial d(t_a^*;t^*)}{\partial t^*} - \frac{\partial^2 d(t_a^*;t^*)}{\partial t^*\partial t_a^*}\right]\right\| \le \left\|\left[(\lambda+r)\frac{\partial 2d(t_a^*;t^*)}{\partial t_a} - \frac{\partial^2 d(t_a^*;t^*)}{\partial t_a^2}\right]\right\|$

Proof: Notice that $\frac{d(t_a^*(t^*)-t^*)}{dt^*} = \frac{dt_a^*}{dt^*} - 1$. By substituting Equation (11), it is clear that $\left[(\lambda+r)\frac{ad(t_a^*;t^*)}{\partial t^*} - \frac{\partial^2 d(t_a^*;t^*)}{\partial t^*\partial t_a^*}\right] \ge \left[(\lambda+r)\frac{\partial d(t_a^*;t^*)}{\partial t_a} - \frac{\partial^2 d(t_a^*;t^*)}{\partial t_a^2}\right]$ is equivalent to $\frac{d(t_a^*(t^*)-t^*)}{dt^*} \le 0$. □

V. OPTIMAL POLICIES ON TECHNOLOGY DISSEMINATION

In the previous sections, we analyzed the market equilibrium of technology

[19] In fact, $dE^*(t^*)/dt^*$ is the marginal externality gain or loss in the economy by delaying the international adoption by one period.

[20] The following condition is rather technical and would not hold when both terms in the first bracket are zero. Hence, the strict concavity of the function is necessary for the lemma.

dissemination. However, the market equilibrium is not necessarily socially efficient considering the public good nature of technology and the strategic behaviors in the international market. In this section we concern ourselves with a society's problem for internalizing positive externalities arising from both international and domestic technology adoption. A policy maker often experiences difficulties choosing a proper instrument to reach the social optimum. Hence, we focus on the case that a policy maker limits its scope of policies on the international technology-adopting sector, Sector A in Country 2. We abstract from a strategic policy game between the two countries. Optimal policies in Country 2 for the timing of technology adoption will be the second best solution, rather than one for a social optimum.[21]

Formally, we define the government's value function, $V_g(\hat{t})$ as the sum of the value of international adoption of a new technology from Country 1, and the value of domestic adoption after a new technology is available in Country 2. That is, from Equations (6) and (10), the government's value function becomes

$$V_g(\hat{t}) = e^{-(\lambda+r)\hat{t}}\left[\frac{\pi_1-\pi_2}{\lambda+r} - c(\hat{t})\right] + E^*(\hat{t}). \tag{13}$$

Using Equations (7) and (12), we will choose the optimal time of international technology adoption by taking account of the effects of its domestic adoption. The first order condition for the government's optimum $\hat{t}$ becomes

$$V_g'(\hat{t}) = e^{(\lambda+r)\hat{t}}\Big\{-(\pi_2-\pi_1) + \Big[(\lambda+r)c(\hat{t}) - c'(\hat{t}) - e^{-(\lambda+r)(t_a^*-\hat{t})}\frac{\partial d(t_a;\,\hat{t})}{\partial t}\Big]\Big\} = 0$$

It is easy to check the second order condition as long as $d(t_a;\,\hat{t})$ is concave in $\hat{t}$. Therefore,

Lemma 4: *The government's second best optimal timing in the interior of* $t_g^* \in (0, \infty)$ *of international technology adoption must satisfy*

$$\pi_2 - \pi_1 = (\lambda+r)c(t_g^*) - c'(t_g^*) - e^{-(\lambda+r)(t_a^*-t_g^*)}\frac{\partial d(t_a(t_g^*);\, t_g^*)}{\partial t_g} \tag{14}$$

when $V_g(\hat{t}) \geq 0$ *for some* $\hat{t} \in (0, \infty)$

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[21] Note that the first best solution is easy to obtain by choosing the timing of both international and domestic adoption. But, at the first best solution, we would be not able to analyze the interdependence of the two timing decisions that we are interested in.

$$\lim_{t^*\to\infty}\left[(\lambda+r)c(t^*)-c'(t^*)-e^{-(\lambda+r)[t_a^*(t^*)-t^*]}\frac{\partial d(t_a;\, t^*)}{\partial t}\right]$$
$$<\pi<(\lambda+r)c(0)-c'(0)-e^{-(\lambda+r)t_a^*(0)}\ \frac{\partial d(t_a;\, 0)}{\partial t}.^{22}$$

Corollary 7: *Assuming an interior solution, the optimal time of international technology adoption is earlier than the equilibrium time of international technology adoption.*

Proof: By Equations (8) and (14),

$$(\lambda+r)c(t^*)-c'(t^*)=(\lambda+r)c(t_g^*)-c'(t_g^*)-e^{-(\lambda+r)(t_a^*-t_g^*)}\frac{\partial d(t_a^*;\, t_g^*)}{\partial t_g}$$

However, the last term is negative and $(\lambda+r)c(t)-c'(t)$ is decreasing in t. Therefore t_g^* and t^* must satisfy $t_g^*<t^*$. □

Hence, the government can improve social efficiency by encouraging international adoption sooner than at the market-equilibrium timing. This corollary is also consistent with Corollary 5. However, the timing of domestic adoption is dictated by the condition in Corollary 6, which implies that Sector B could delay the adoption and thereby the government policy can intensify the sectoral differences in the levels of technology.

The government's problem in Country 2 is to induce Sector A to choose the socially desirable timing of technology adoption. One way to implement such an objective is a direct lump-sum subsidy plan. The amount of lump-sum transfer to Sector A becomes E^* in Equation (10). However, this subsidy plan is not unique, since any vertical transformation of $E^*(t)$ will serve the government's objective provided that the resulting benefit to the buying sector is positive, i.e., $E^*(t)+k$, where k is such that the value of $\max_t V_g(t)+E^*(t)+k$ is positive. Furthermore, implementation of such a lump-sum subsidy is difficult and easily leads to strategic behaviors, which can cause additional distortionary effect between Sector A and B.

An alternative to the government's subsidy policy is to set an economy-wide interest rate. We consider an interest rate which can implement the above second-best optimal time, t_g^*. The following proposition simply illustrates that a government can improve social efficiency by setting a triggered interest rate

[22] Otherwise, we may have the corner solutions for the optimal policy: $t_g^*=0$ when $V_g(0)>0$ and $\pi>(\lambda+r)c(0)-c'(0)-e^{-(\lambda+r)t_a^*}\frac{\partial d(t_a;\, 0)}{\partial t^*}$. On the other hand, $t_g^*=\infty$ when $V_g(\hat{t})<0$ for all $\hat{t}\in[0,\infty)$, or $\pi<\lim_{t^*\to\infty}\left[(\lambda+r)c(t^*)-c'(t^*)-e^{-(\lambda+r)[t_a^*(t^*)-t^*]}\frac{\partial d(t_a;\, t^*)}{\partial t^*}\right]$.

lower than the market interest rate.[23] That is, the second best interest rate is as follows:

Proposition 3: *There exists a triggered interest rate r^* which induces buying Sector A to choose the timing for international technology adoption. That is, with the market interest rate r,*

$$r^* = r - e^{-(\lambda+r)(t_a^* - t_g^*)} \frac{\partial d(t_a^*;\, t_g^*)}{\partial t_g} \left(\frac{1}{c(t_g^*)} \right)$$

Proof: Such an r^* should satisfy $t_g^* = \arg \underset{t}{Max}\ V_g(t_g) = \arg\ Max\ V(t)$. By Equations (8) and (13), r^* also satisfies that

$$(\lambda+r)c(t_g^*) - c'(t_g^*) - e^{-(\lambda+r)(t_a^* - t_g^*)} \frac{\partial d(t_a^*;\, t_g^*)}{\partial t_g} = (\lambda+r)c(t_g^*) - c'(t_g^*).$$

Therefore, $r^* = r - e^{-(\lambda+r)(t_a^* - t_g^*)} \dfrac{\partial d(t_a^*;\, t_g^*)}{\partial t_g} \left(\dfrac{1}{c(t_g^*)} \right)$. □

Notably, the government needs to set the triggered interest rate lower than the market interest rate. Actually, in some developing countries, a government targets different interest rates to different industries or firms for various purposes.

VI. 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 game-theoretical setting, we found that a convex-combination price bargaining rule makes the buyer's and the seller's problem equivalent. Hence, the average price rule simplifies the decision problems, and we investigated an open-loop equilibrium.

First, considering the dynamic problem of technology evolution over a longer period, we showed that rapid technical change in the current generation delays adoption of current technologies; this in turn has a negative effect on the speed of technical progress in the next generation. Second, the comparative advantage we employed in our analysis is the wage differential between countries, but it can be extended to other cases such as the difference in the stock of old-vintage capital equipment between countries. Third, the market outcome of

[23] Note that we would not suggest that the triggered interest policy is superior to the lump-sum subsidy policy. We are more interested in whether the interest policy will leads the triggered interest rate higher or lower than the market interest rate.

international technology adoption is not efficient due to the knowledge spillover arising from domestic technology diffusion in the buying country. Technology dissemination is more active after the technology is domestically possessed than before. Finally, in our model with heterogeneous sectors, we found that the adoption of a technology is positively related to the adoption time of the technology, and negatively related to the resulting positive spillover. And also, the private optimal timing is later than the socially desirable timing of adopting a new technology. This suggests government policies that can improve social welfare.

The basic model in this paper is general enough to provide many avenues for extending our analysis. We could introduce more than one firm in the technology-adopting sector, so that we might investigate some interesting questions by including, for example, a rivalry outcome among technology buyers, 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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