NBER WORKING PAPERS SERIES

PATENT RACES, PRODUCT STANDARDS, AND INTERNATIONAL COMPETITION

Richard Jensen

Marie Thursby

Working Paper No. 3870

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
October 1991

The authors thank Ward Hanson, Kala Krishna, Katharine Rockett, Bob Staiger and participants of the NBER Summer Institute and University of Western Ontario Conference on International Trade for insightful comments. Jensen's research was made possible by a Summer Research Grant from the College of Business and Economics of the University of Kentucky. The grant was made possible by a donation of funds from Ashland Oil, Inc. Thursby's research is partially funded by the Center for the Management of Manufacturing Enterprises, Krannert Graduate School of Management. This paper is part of NBER's research program in International Studies. Any opinions expressed are those of the authors and not those of the National Bureau of Economic Research.

NBER Working Paper #3870
October 1991

PATENT RACES, PRODUCT STANDARDS, AND INTERNATIONAL COMPETITION

ABSTRACT

We examine anticipatory product standards intended to improve the strategic position of firms in an international patent race where firms do R&D to develop products that are close substitutes. The effects of a standard are shown to depend on the way the standard is specified, which firm develops which product, and on the order in which products are discovered. Simple standards are, in general, time inconsistent because of consumer losses that occur when products ruled out by the standard are discovered before the product set as the standard. A state contingent standard is shown to be time consistent when compulsory licensing by the foreign firm is introduced.

Marie Thursby
Department of Economics
Purdue University
West Lafayette, IN 47907-1310
and NBER

Richard Jensen
Department of Economics
University of Kentucky
Lexington, KY 40506-0034

1. Introduction

International R&D competition often results in outcomes where several firms develop and patent products that are close substitutes. In this situation, it is not uncommon for governments to set anticipatory standards intended to improve the strategic (competitive) position of their firms. This paper examines the impact of such standards, and shows that in a dynamic, uncertain environment, the use of simple, anticipatory standards is problematic. The welfare effects of a standard are shown to depend on the way the standard is specified, but more importantly on which firm develops which product and on the order in which products are discovered. We show that simple standards are, in general, time inconsistent. Even if a standard increases welfare after all products are discovered, it still can reduce *ex ante* expected welfare because consumers are hurt when products ruled out by a simple standard are discovered before the discovery of the product set as the standard. Thus the only type of standard which can unambiguously increase welfare in a dynamic, uncertain environment is one that is complicated in the sense that it is state-contingent.[1]

Understanding the effects of product standards is important because the Technology Policy Task Force has recommended the use of standards to "support U.S. industry in technology development (Technology Task Force, 1988, p. 18)."[2] The creation of the Task Force and its recommendations were prompted by concern over the performance of U.S. high-technology industries. Since 1980 the U.S. trade surplus in high-technology products has fallen, and the share of foreign companies in U.S. patent registrations has steadily risen.[3] U.S. companies appear to be dropping behind in patent races in industries they once dominated. For example, the U.S. market share in consumer electronics has fallen from 100% in 1970 to less than 5% (Technology Policy Task Force (1988)), and U.S. firms appear to be behind in the race to develop high definition television (HDTV). Similar examples can be found in other high tech industries (Wysocki (1988)).

One example of a standard is one requiring new products to be compatible with existing ones, such as the Federal Communication Commission's regulation that HDTV transmission in the United States be compatible with existing broadcasting channels. This was generally considered to have been a strategic move to improve the position of U.S. firms trying to develop HDTV, because it meant the Japanese MUSE system could not be used in the U.S. without adaptation (Sims (1988)). When the standard was announced (September 1988), the Japanese MUSE system was in working prototype. Zenith was developing a retrocompatible version, but it was only in the theoretical stage of development and was generally considered to be inferior to the Japanese version. Hence, retrocompatibility was, in effect, a standard based on the product being developed domestically. The move was considered strategic because its announced intention was to alter the Japanese advantage in the race.

The United States is not alone in this type of standard setting. As is well documented by Crane (1978), Europe never adopted a single color TV standard because individual governments promoted standards to protect the interests of their firms. Hazard and Daems (1988) and Pelkmans and Beuter (1987) also make it clear that the European position on HDTV standards has the same motivation.

This paper examines the impact of standards set for strategic reasons before products are successfully developed. In order to examine such policies, it is important to model both the racing aspect of international R&D competition and the simultaneous development of different products by rival firms. In Section 2, we present a model of uncertain R&D between a foreign and a domestic firm where the foreign firm has an advantage in developing the superior of two closely related products. Whether firms race for the same patent, pursue different patents simultaneously, or the lagging firm drops out is determined endogenously in this model. This allows us to examine the impact of a standard imposed before the end of the race. In the absence of policy, the unique subgame perfect equilibrium (SPE) involves the foreign and domestic firm simultaneously pursuing different patents if the foreign firm has a sufficiently large advantage. In this model, dropping out is never subgame perfect in the absence of policy if pursuing an alternative patent has positive expected return for the lagging firm.

In Sections 3 and 4, we show that the imposition of a standard can alter these outcomes in several ways. In Section 3, we examine the impact of the lagging firm's government imposing a standard based on the product being developed domestically. We show it is more likely that both firms will race to develop the same patent (in particular, the one being developed domestically). Some of the more interesting effects, however, arise when the foreign and domestic firms still pursue different patents in equilibrium. We show that the standard need not be welfare improving *ex ante* in this case even if it is certain to improve welfare after both products are discovered. That is, expected welfare can still be lower because the standard benefits a domestic firm only after its R&D has succeeded, but consumers suffer losses after the foreign firm succeeds. Hence, if the foreign firm succeeds first, losses suffered by consumers before the domestic firm succeeds can outweigh the gains from this policy after the domestic firm succeeds. This shows that the imposition of a standard can be time-inconsistent in two ways. It may not be optimal to impose it before either product is discovered, but optimal to impose it if the domestic firm discovers the inferior product first. Also, it may be optimal to impose it before either product is discovered, but then remove it if the foreign firm succeeds in developing the superior product first.

In the latter case, the announced standard has limited credibility. Firms may well expect the lagging firm's government to remove the standard if the foreign firm discovers its product first. The FCC, for example, reversed its decision on a color TV standard in the fifties once a superior system was developed.[4] Thus, in Section 4, we consider the effect of a domestic policy that includes a contingency to adopt the foreign product as a standard once it is discovered. To capture common licensing practices,[5] the contingency includes a requirement that the foreign firm license its patent to the domestic firm at a minimal fee. An interesting aspect of this policy is that in equilibrium the lagging firm may drop out of the race and wait to acquire a license from the foreign firm. The policy is shown to be time consistent whether or not the lagging firm drops out. That is, when licensing occurs, domestic expected welfare is higher at every date than it would be with no policy. In Section 5 we compare the contingent standard and the domestic standard for an example with linear demand and constant marginal cost. Section 6 concludes.

Our work differs from the literature on compatibility standards in two important ways. First, we examine the impact of a standard imposed before the successful completion of R&D. Farrell and Saloner (1985 and 1986a) and Katz and Shapiro (1986a and b) focus on the relation of compatibility and innovation, but they address issues related to adoption of exogenously developed technologies which are currently available. Second, we focus on international competition. Besen and Saloner (1989), David (1987), and Farrell and Saloner (1988) discuss coordination problems involved in international standard setting, and Crane (1979), Pelkmans and Beuter (1987), and Hazard and Daems (1988) discuss the use of television standards as nontariff trade barriers to trade. Lecraw (1987) discusses Japanese standards for a wide range of products as trade barriers.[6] However, theoretical models have abstracted from international issues, so that welfare comparisons in the existing literature examine the profits and consumer surplus of all firms and consumers. To understand unilateral policies, such as the recent FCC regulation, it is important to determine profits and surplus of domestic residents, as we do in this policy analysis.

Our work also differs from studies of patent races that have generally analyzed models in which identical firms compete for the same patent (see Reinganum (1989) for an excellent survey). One exception is the literature on sequences of races, in which firms compete for the same patent, but are not identical because the winner of the preceding race earns greater profit during the current race. Another exception is the literature on preemption and leapfrogging. Fudenberg, Gilbert, Stiglitz, and Tirole (1983, hereafter FGST) analyze several related models in which one firm has an advantage in a race for the same patent. In one of these models the firm behind drops out of the race immediately (and the leader does R&D until discovery). In the others, the laggard will not only stay in the race, but also may be able to leapfrog into the leadership role if the R&D process involves two distinct stages with random discovery or if there is imperfect monitoring of the rival's R&D effort. Lippman and McCardle (1988) show that if the decision to do R&D is made at discrete dates, then laggard drops out only if its rival has a large enough lead. This paper contributes to this literature by showing a laggard will not drop out if it can develop a related, though inferior, patent.

Several of the issues we raise are addressed in the international trade literature. Dixit (1988a and b), Bagwell and Staiger (1989), and Beath (1990) examine international R&D competition in the context of patent races. Although they allow asymmetries among firms, these studies consider firms racing to develop the same product. Krishna (1988) and Yanagawa (1990) examine trade policy in the presence of compatibility issues, but they do not examine the use of standards or explicitly consider R&D issues. Finally, Staiger and Tabellini (1987) examine the time consistency of international trade policy, but they do not address R&D or standards issues.

2. A Model of Uncertain R&D With Substitutes

Consider a two country world in which a domestic and a foreign firm choose whether or not to do R&D to develop a new product A. R&D is risky because the date of discovery is stochastic, and because winning the patent for A does not prevent the development of a close, but imperfect, substitute for A. That is, winning the patent for A does not guarantee monopoly in the standard sense because there is a close substitute for A that can be developed. This can occur if patent protection is imperfect, as is often the case across countries. It can also occur if there are many substitutes for A which are different from the view of patent law, so it is not feasible to obtain patents for all of them (see Gilbert and Newbery (1982) for a thorough discussion of this possibility).

Each firm can also do R&D to develop a new product B which is a close, but imperfect, substitute for A. Further assume A is superior to B in that each firm would prefer to win the patent for A. To keep the analysis tractable, assume neither firm can, or will, try to develop both A and B. Scarcity of trained researchers and research facilities can imply that conducting two R&D programs simultaneously either reduces the probability of success in each program, or increases the cost of R&D in each program, or both. In this event each firm conducting only one R&D program at a time can be derived as an equilibrium outcome, although we do not do so in order to avoid complicating the analysis unnecessarily. If, as noted above, it is infeasible to patent all of the close substitutes for A, the firm that has the patent for A cannot prevent its rival from developing some substitute. Therefore, there is no loss of generality in dealing with only two products, A and some substitute, B.

Let $\pi_i(A) = \sum_{m=1}^{2} \pi_i^m(A)$ be the total flow profit earned by firm i if it has discovered A but B has not been discovered, where π_i^m is firm i's flow profit from country m. Let $\pi_i(A;B) = \sum_{m=1}^{2} \pi_i^m(A;B)$ be the flow profit earned by firm i if it has discovered A and B has been discovered. Define $\pi_i(B)$ and π_i (B;A) analogously. Then the assumption

$$\text{(A1)} \quad \pi_i^m(A) > \max\{\pi_i^m(B), \pi_i^m(A;B)\} \text{ and } \pi_i^m(B;A) < \min\{\pi_i^m(B), \pi_i^m(A;B)\}$$

embodies both the notion that A and B are substitutes and that A is superior to B in each market. We assume markets are segmented and that in the absence of government policy, profits in each market are positive (i.e., $\pi_i^m(\bullet) > 0$). Then (A1) implies both $\pi_i(A) > \pi_i(A;B)$ and $\pi_i(B) > \pi_i(B;A)$, and $\pi_i(A) > \pi_i(B)$ and $\pi_i(A;B) > \pi_i(B;A)$. Under this specification of R&D, (A1) guarantees the expected return from discovering A is greater than that from discovering B when the R&D costs of A and B are the same. Also note this does not assume A is superior enough to B in production that $\pi_i(A;B) > \pi_i(B)$. Having a monopoly with B may provide greater profit than producing A when B is available. This profit ranking can hold with a variety of differentiated product models, including Shaked and Sutton's (1982) vertically differentiated demand structure and models with network externalities and variety (Farrell and Saloner (1986b)).

The discovery date of each new product is assumed to be stochastic and exponentially distributed with parameter μ, so that if either firm does R&D, the probability it will discover the new product between times t and t + dt is μdt. Firms incur a constant flow cost of development, and these costs may differ by firm as well as the product being developed. Firm i must pay a constant flow cost $k_{iA} > 0$ to do R&D on A or a constant flow cost $k_{iB} > 0$ to do R&D on B (i = 1,2). Then firm i has an advantage relative to firm j in developing A if $k_{iA} < k_{jA}$. This is the most tractable way of giving one firm an advantage in doing R&D on A. This modeling choice is not crucial because the analysis can be generalized to hazard rates that differ among firms or innovations, or that depend on accumulated R&D experience, as in FGST (1983) and Lippman and McCardle (1988).

Because we are interested in subgame perfect equilibria (SPE), we must construct payoffs which incorporate optimal behavior by the remaining firm after its rival has discovered A or B. First, suppose A is discovered by firm i, but B has not been discovered. Then firm j ($j = 1,2$, $j \neq i$) can either drop out or do R&D on B. If it drops out it earns 0. If it does R&D on B, it pays flow cost k_{jB} until it succeeds, and earns $\pi_j(B;A)$ thereafter. Hence, the expected return from R&D on B, discounted back to the discovery date of A, is

$$S_{jB} = [(\mu/r)\pi_j(B;A) - k_{jB}]/(r + \mu). \tag{1}$$

where S_{jB} is used to denote the fact that B is the second product discovered (by j) and r is the common discount rate. Note that the assumption

(A2) $(\mu/r)\pi_j(B;A) > k_{jB}$ for $j = 1,2$

guarantees that B will be developed even if A is available.

Similarly, firm i earns $\pi_i(A)$ in each period after A is discovered, but before B is discovered, and $\pi_i(A;B)$ in each period after B is discovered. Hence, firm i's expected return from A, discounted back to its discovery date, is

$$F_{iA} = [\pi_i(A) + (\mu/r)\pi_i(A;B)]/(r + \mu). \tag{2}$$

The notation F_{iA} denotes that A is the first process discovered (by i).

If B is discovered first by firm i, then firm j can either drop out and earn 0 or do R&D on A and earn the expected return (discounted back to the discovery of B)

$$S_{jA} = [(\mu/r)\pi_j(A;B) - k_{jA}]/(r + u). \tag{3}$$

The assumption

(A3) $(\mu/r)\pi_j(A;B) > k_{jA}$ for $j = 1,2$

guarantees that A will be developed even if B is available. As noted above, (A1) implies $S_{jA} > S_{jB}$ if $k_{jB} = k_{jA}$ (superiority of A in production implies its superiority in development if the flow costs are the same). Firm i's expected return from B, discounted back to its discovery date, is

$$F_{iB} = [\pi_i(B) + (\mu/r)\pi_i(B;A)]/(r + \mu). \tag{4}$$

Notice (A1) also implies $F_{iA} > F_{iB}$. More importantly, there is an incentive for a firm at a disadvantage in a race for A to begin trying to develop B immediately, rather than race for A and develop B if it loses the race. If it discovers B first, it earns monopoly profit $\pi_i(B)$ until A is discovered.

Assume the R&D game begins at t = 0. Optimal behavior after discovery of A or B is given above. Let a denote the strategy of doing R&D on A until its discovery (by either firm), b denote the strategy of doing R&D on B until its discovery (by either firm), and d denote the strategy of doing nothing unless and until discovery of A or B by the rival. Assuming that the discovery dates for A and B are exponentially distributed with constant parameter μ allows the strategies and payoffs for this game to be specified in a simple way. In particular, reduced-form payoffs can be computed and the game can be analyzed as if it were a one-shot game. Table 1 gives the expected payoffs to firm 1 for all possible strategies of firm 2. We omit the payoffs to firm 2 because they are defined analogously.

It is easy to see from these payoffs that delaying R&D cannot be an equilibrium in this model.[7] This is because (A2) and (A3) ensure that a firm's expected return to doing R&D on either A or B is greater than the return to delaying, regardless of its rival's strategy. As long as discovering either product has a positive expected return, then it is surely better for a firm to begin R&D immediately because there is a chance it will discover its product first. Therefore the only question question is whether a firm conducts R&D on A or B. From Table 1, one can see that $\mu(F_{1A} - F_{1B}) > k_{1A} - k_{1B}$ implies that firm 1 will do R&D on A regardless of firm 2's strategy. This condition simply says that firm 1's expected flow return from being first to discover A, net of the flow cost of R&D, is greater than that from being first to discover B. Conversely, if $\mu(F_{1A} - F_{1B}) < k_{1A} - k_{1B}$, then firm 1's expected flow return from being first to discover B (net flow cost of R&D) exceeds that from A, and firm 1 will do R&D on B regardless of firm 2's strategy. Analogous arguments apply to firm 2, so that the results of Theorem 1 follow immediately. Formal proofs of this theorem and all remaining ones in the paper, are given in the Appendix.

<u>Theorem 1</u>. *Under (A1)-(A3), delaying is never a SPE. Moreover:*

(i) *(a,a) is the unique SPE if and only if* $k_{iA} - k_{iB} < \mu(F_{iA} - F_{iB})$ *for* $i = 1,2$.

(ii) *(a,b) is the unique SPE if and only if both* $k_{1A} - k_{1B} < \mu(F_{1A} - F_{1B})$ *and* $k_{2A} - k_{2B} > \mu(F_{2A} - F_{2B})$.

(iii) *(b,a) is the unique SPE if and only if both* $k_{1A} - k_{1B} > \mu(F_{1A} - F_{1B})$ *and* $k_{2A} - k_{2B} < \mu(F_{2A} - F_{2B})$.

(iv) *(b,b) is the unique SPE if and only if* $k_{iA} - k_{iB} > \mu(F_{iA} - F_{iB})$ *for* $i = 1,2$.

(v) *There are multiple SPE and SPE in randomized strategies only if* $k_{iA} - k_{iB} = \mu(F_{iA} - F_{iB})$ *for at least one i.*

Figure 1 is a convenient way to describe the results in Theorem 1. The lines $\mu(F_{1A} - F_{1B}) = k_{1A} - k_{1B}$ and $\mu(F_{2A} - F_{2B}) = k_{2A} - k_{2B}$ divide the space into four quadrants, where equilibria are as indicated. These lines intersect at I, where $k_{iA} - k_{iB} > 0$ for both i, because (A1) implies that it is better to be first to develop A than B, $F_{iA} > F_{iB}$. Notice that the equilibrium of this game is unique for all values of parameters such that $k_{iA} - k_{iB} \neq \mu(F_{iA} - F_{iB})$ for both i = 1,2. The reason for this is that a is firm i's strongly dominant strategy if and only if $k_{iA} - k_{iB} < \mu(F_{iA} - F_{iB})$, and b is firm i's strongly dominant strategy if and only if $k_{iA} - k_{iB} > \mu(F_{iA} - F_{iB})$. Because the set of parameter values such that either $k_{1A} - k_{1B} = \mu(F_{1A} - F_{1B})$, $k_{2A} - k_{2B} = \mu(F_{2A} - F_{2B})$, or both has measure zero (in the set of all possible parameter values in the plane), this game has a unique subgame perfect equilibrium generically.

As is clear from Figure 1, whether or not one firm has an advantage over the other in developing a product depends on the flow costs of R&D. The easiest way to see this is to observe that, if flow R&D costs are the same for both firms and products, then $k_{1A} - k_{1B} = k_{2A} - k_{2B} = 0$. The corresponding point in the figure is the origin, and (a,a) is the unique SPE. However, if firm 1 is given a large enough advantage in developing A (by increasing k_{2A} enough), then the point ($k_{1A} - k_{1B}$, $k_{2A} - k_{2B}$) in the figure moves upward along the $k_{2A} - k_{2B}$ axis until (a,b) is the unique SPE. The latter equilibrium is the most interesting one for our purposes. Not only is it consistent with the observation that firms often race to develop imperfect substitutes, but also it allows us to examine the impact of product standards announced before products are developed.

3. A Standard Based on the Domestic Product

In this section, we assume firm 1 is owned by residents of country 1 and and that its advantage in developing A is large enough that (a,b) is the unique SPE in the absence of government standards. To consider the strategic use of standards, we assume firm 2 is owned by residents of country 2 and that its government sets B as a domestic standard, so that A cannot be sold in its market (without adaptation). We show that setting such a standard before the successful completion of R&D may not increase country 2's expected welfare even if it is certain to improve welfare at the end of the game.

Let the superscript p denote a variable when B is the standard, so that firm i's total flow profit under this policy is denoted by $\pi_i^p(\bullet)$. Because A cannot be sold in country 2 under this policy, $\pi_i^p(A) = \pi_i^1(A) < \pi_i(A)$ and $\pi_i^p(A;B) = \pi_i^1(A;B) < \pi_i(A;B)$. As long as country 1's government is inactive, $\pi_i^p(B) = \pi_i(B)$ because B can be sold in each market. The flow profit from B when A is available increases under the policy because the firm selling B in country 2 earns monopoly profit from that market. That is, $\pi_i^p(B;A) = \pi_i^1(B;A) + \pi_i^2(B) > \pi_i(B)$. Notice that this presumes an adapter cannot be developed to bring A in line with the standard. If an adapter could be developed, which would not increase A's production cost, then the standard would have no effect. If an adapter could be developed, but was costly to produce, then the standard would have the same qualitative effects as it does in this analysis.

Thus this policy has the effect of decreasing the return to discovering A and increasing the return to discovering B for both firms. This implies $S^p_{iA} < S_{iA}$, so that in order to ensure A is developed, (A3) must be strengthened to

(A3)′ $(\mu/r)\pi^p_j(A;B) > k_{jA}$ for j = 1,2.

It also implies $S^p_{iB} > S_{iB}$, so that (A2) still ensures that B is developed. Finally it implies $F^p_{iA} < F_{iA}$ and $F^p_{iB} > F_{iB}$ for both firms, so that (a,b) is now less likely, and (b,b) is more likely, to be the SPE of the R&D game. In terms of the figure, the standard causes the lines to shift so that the point I is northwest of its location in the absence of policy.

<u>*Theorem 2*</u>. *Under (A1), (A2), and (A3)′ the unique SPE with this standard is*

(i) *(a,b) if and only if both* $k_{1A} - k_{1B} < \mu(F^p_{1A} - F^p_{1B})$ *and* $k_{2A} - k_{2B} > \mu(F^p_{2A} - F^p_{2B})$, *and*

(ii) *(b,b) if and only if and* $k_{iA} - k_{iB} > \mu(F^p_{iA} - F^p_{iB})$ *for i = 1,2.*

Moreover, suppose that absent this standard, the SPE is firm 1 develops A and firm 2 develops B. Then under this standard, the SPE is less likely to be that firm 1 develops A and firm 2 develops B, and more likely to be that the firms race for B.

Although the SPE may change, for purposes of comparison we assume throughout the paper that the SPE is firm 1 develops A and firm 2 develops B with or without the standard. It follows immediately from Theorems 1 and 2 that, with or without the standard, the unique SPE is firm 1 develops A and firm 2 develops B if and only if

$$k_{1A} - k_{1B} < \mu(F^p_{1A} - F^p_{1B}) \text{ and } k_{2A} - k_{2B} > \mu(F_{2A} - F_{2B}). \tag{5}$$

We would expect this outcome, for example, firm 1's cost advantage is sufficiently large or if country 2's market is small relative to the total market for A.[8]

It is clear that firm 1 loses and firm 2 gains from B as a standard. However this does not imply that welfare changes in the same directions because flow welfare in a country is its firm's flow profit plus its flow consumer surplus. Let flow consumer surplus in country i in the absence of policy be $C_i(A)$ if only A has been discovered, $C_i(B)$ if only B has been discovered, and $C_i(A,B)$ if both have been discovered. With only two firms, a natural assumption to make is

(A4) $C_i(A,B) > C_i(A) > C_i(B)$.

The last inequality embodies the notion that A is superior to B for consumers in both countries, while the first implies consumers as a group are better off with duopoly competition when both A and B are available than when only one of them is sold by a monopolist. Under the standard, we assume

(A5) $C_1^p(A) = C_1(A), C_1^p(B) = C_1(B)$, and $C_1^p(A,B) = C_1(A,B)$, and

(A6) $C_2^p(A) = 0 < C_2(A), C_2^p(B) = C_2(B)$, and $C_2^p(A,B) = C_2(B)$.

(A5) says the standard does not change consumer surplus in country 1 because A and B can still be sold there. Given (A4), (A6) says the standard lowers consumer surplus in country 2 once A is discovered because it cannot be sold there. Notice that (A4) does not contradict the usual consumer surplus rankings of competitive models with network externalities, where a standard of A or B might be preferred to both products being available at price equal to marginal cost. Consumers in this model prefer variety (i.e. both A and B available) because there is increased competition if both are available.

There are three times at which welfare comparisons can be made: the beginning of the game (t = 0); the first discovery date; and the second discovery date (i.e., when both have been discovered). Suppose firm 1 succeeds first. Then in the absence of policy, expected welfare, discounted back to the discovery date of A, in each country is

$$W_1(F_{1A}) = [\pi_1(A) + C_1(A) + (\mu/r)[\pi_1(A;B) + C_1(A,B)]]/(r + \mu) \text{ and} \tag{6}$$

$$W_2(S_{2B}) = \{C_2(A) + (\mu/r)[\pi_2(B;A) + C_2(A,B)] - k_{2B}\}/(r + \mu). \tag{7}$$

Similarly, if firm 2 succeeds first, then expected welfare, discounted back to the discovery date of B, in each country is

$$W_1(S_{1A}) = \{C_1(B) + (\mu/r)[\pi_1(A;B) + C_1(A,B)] - k_{1A}\}/(r + \mu) \text{ and} \tag{8}$$

$$W_2(F_{2B}) = \{\pi_2(B) + C_2(B) + (\mu/r)[\pi_2(B;A) + C_2(A,B)]\}/(r + \mu). \tag{9}$$

Initial expected welfare (at $t = 0$) is defined analogously to the expected firm payoffs; that is,

$$W_1(a,b) = [\mu W_1(F_{1A}) + \mu W_1(S_{1A}) - k_{1A}]/(r + 2\mu) \text{ and} \tag{10}$$

$$W_2(a,b) = [\mu W_2(F_{2B}) + \mu W_2(S_{2B}) - k_{2B}]/(r + 2\mu). \tag{11}$$

Expressions for expected welfare under the standard are defined analogously to (6)-(11) with $\pi_i^P(\bullet)$ and $C_i^P(\bullet)$ replacing $\pi_i(\bullet)$ and $C_i(\bullet)$. Under our assumptions it is clear that the standard lowers expected welfare in country 1 at all three dates. However, the effect of the standard on expected welfare in country 2 is less clear. Firm 2 gains after both A and B are discovered because it is always a monopolist in its own market, $\pi_2^P(B;A) > \pi_2(B;A)$. But consumers lose after A is discovered because they cannot consume it, $C_2^P(A) = 0 < C_2(A)$ and $C_2^P(A,B) = C_2(A) < C_2(A,B)$. Although the net effect is ambiguous, some conclusions can be drawn. Suppose that, after both A and B are discovered, the standard hurts consumers more than it benefits firm 2, $C_2(A,B) - C_2(A) > \pi_2^P(B;A) - \pi_2(B;A)$, so flow welfare is lower. Then expected welfare at the first discovery date is also lower whether A or B is discovered first, $W_2(F_{2B}^P) < W_2(F_{2B})$ and $W_2(S_{2B}^P) < W_2(S_{2B})$, and therefore initial expected welfare is lower under this standard, $W_2^P(a,b) < W_2(a,b)$.

<u>*Theorem 3*</u>. *Assume the imposition of a compatibility standard by country 2 hurts its consumers more than it benefits its firm, and therefore reduces flow welfare after both A and B are discovered. Then the standard also reduces country 2's initial expected welfare and its expected welfare at the first discovery date whether A or B is discovered first.*

Now suppose instead that, after A and B are discovered, the standard benefits firm 2 more than it hurts consumers, so flow welfare is higher. Then expected welfare at the first discovery date is higher under the standard if B is discovered first, $W_2(F_{2B}^P) > W_2(F_{2B})$. However, this policy still has an ambiguous effect on expected welfare at the first discovery date if A is discovered first, and thus on initial expected welfare as well. This is particularly interesting because it shows that imposition of a compatibility standard may not be a time consistent policy. By a time consistent policy we mean one that increases expected welfare, compared to that with no policy, at every date.

Theorem 4. *Assume the imposition of a compatibility standard by country 2 benefits its firm more than it hurts its consumers, and thus increases flow welfare after both A and B are discovered. Then this policy can also increase both initial expected welfare and expected welfare at the first discovery date. However, it can also be time inconsistent in two ways.*

(i) It can increase initial expected welfare, decrease expected welfare at the first discovery date if A is discovered first, and then increase flow welfare after B is also discovered.

(ii) It can decrease initial expected welfare, increase expected welfare at the first discovery date if B is discovered first, and then increase flow welfare after A is also discovered.

That this standard increases flow welfare in country 2 after both A and B are discovered can, but need not, imply that it always increases expected welfare in country 2 before both are discovered. It implies only that expected welfare at the first discovery date is higher if B is discovered first. The standard can increase or decrease expected welfare at the first discovery date if A is discovered first and initial expected welfare. The intuition is simply that the standard hurts consumers after A is discovered, but helps firm 2 only after both A and B are discovered. If B is discovered first, then the only effect occurs after both have been discovered, when welfare is higher with the standard (by assumption in this case). However, if A is discovered first, then consumers are hurt thereafter, but firm 2 benefits only after it discovers B. Consumers' expected loss between the discovery times of A and B may be large enough to outweigh the flow welfare increase after B is discovered. If so, expected welfare at the date A is discovered is lower with the standard. In fact, this interim loss may be large enough that initial expected welfare is also higher with the standard.

Although it is more natural to think of country 2's government setting B as a standard, it is worth considering the effect of A as a standard. The government might well think that imposing A as a standard could induce firm 2 to race for the superior product. It is straightforward to show that (a,a) is more likely to be the equilibrium with A as a standard. This is because A as a standard in country 2 increases the expected return to either firm from being the first to discover A, and it decreases the expected return to either firm from being second to discover B. However, with uncertain R&D it is not clear that firm 2 will win the race or that welfare will improve. Moreover, firm 2 may have enough of a disadvantage in R&D on A that (a,b) remains the equilibrium, in which case both firm 2 and consumers in country 2 lose. Firm 2 loses because it can't sell B in its own market (without an adaptor). Consumers lose for the same reason they lose with B as a standard. If B is discovered first, they lose between the first and second discovery dates because they cannot consume the product. They lose at the end of the race because A is sold by a monopolist rather than both A and B being sold by duopolists.

These results suggest that setting anticipatory standards can be problematic, regardless on which standard is set. The results are driven, in part, by the uncertain discovery dates, but they occur, in part, because either standard creates a monopoly in country 2 even after both products are discovered. Thus, even with a standard based on the superior product, A, consumers would prefer duopoly competition if both A and B are available.

4. Toward a Time-Consistent Standard

Suppose country 2's government decides to set A as a standard if it is discovered by firm 2 or if firm 1 discovers it and licenses the patent to firm 2 at a fixed fee (set by the government). If firm 1 discovers A, but does not license the patent, B is set as a standard once it is discovered. Although this policy seems complicated, the results in Section 3 show that contingencies such as this may be necessary to design an anticipatory policy that would unambiguously improve welfare. This particular policy is consistent with the strategic motive to improve firm 2's competitive position in the race because it benefits firm 2 regardless of which product is discovered first. As we shall show in this section, it can also benefit consumers in country 2 (relative to either of the standards considered in Section 3) because of duopoly competition when licensing occurs.

We continue to assume (5) so that (a,b) is the unique SPE in the absence of policy and when B is the standard. In addition, we focus on the case where B as a standard benefits firm 2 more than it hurts consumers in country 2 once both products are discovered.[9] This entails no loss of generality since it is the only case in which B as a standard is time inconsistent. The time inconsistency arises only because, even though the standard increases flow welfare after both products are discovered, consumers in country 2 lose forever if A is discovered first, but firm 2 gains only after B is discovered. Therefore, a time consistent policy must have the property that both firm 2 and consumers in country 2 benefit from it whichever product is discovered first.

We shall refer to the game with B as a standard as the p game and to the game with A as a contingent standard as the c game. Suppose A is discovered first by firm

1 in the c game. Then firm 1 can either offer a license to firm 2 at fee L, in which case firm 2 can buy the license or not, or not offer a license. If firm 1 offers a license at fee L and firm 2 buys, then firm 1's expected return is

$$F^{c}_{1A} = [\pi_1(A;A)/r] + L, \tag{12}$$

and firm 2's expected return is

$$S^{c}_{2B} = [\pi_2(A;A)/r] - L \tag{13}$$

where $\pi_i(A;A)$ is firm i's flow duopoly profits from selling A in both markets. If firm 1 does not license the patent, then country 2's government will not enforce B as the standard until it's discovery because it is not credible to do so. Therefore, if firm 1 does not license, its expected return is

$$F^{n}_{1A} = [\pi_1(A) + (\mu/r)\pi^{p}_{1}(A;B)]/(r+\mu), \text{ and} \tag{14}$$

firm 2's expected return is

$$S^{n}_{2B} = [(\mu/r)\pi^{p}_{2}(B;A) - k_{2B}]/(r+\mu). \tag{15}$$

The assumption

(A7) $(r/\mu) < [\pi_1(A;A) - \pi^{p}_{1}(A;B)]/[\pi_1(A) - \pi_1(A;A)]$

is sufficient to guarantee that firm 1 will offer a license for any nonnegative fee (i.e., $F^{c}_{1A} > F^{n}_{1A}$ for any $L \geq 0$). Notice that in order for (A7) to hold, firm 1's profit from selling A in both markets when it has licensed A must exceed its profit from its own market when A and B are both available. In this case (A7) holds for a high enough hazard rate because increasing the hazard rate speeds up the expected discovery date of B, and thus reduces the length of time firm 1 can earn monopoly profit from A in both markets. The assumption

(A8) $\pi_2(A;A) > \pi^{1}_{2}(B;A) + \pi^{2}_{2}(B) = \pi^{p}_{2}(B;A)$

is sufficient to guarantee that firm 2 will buy a license at a minimal positive fee (i.e., $S^{c}_{2B} > S^{n}_{2B}$ for a sufficiently small but positive fee L). This condition simply says flow profit if it buys the license exceeds flow profit under the standard when A is available.[10]

Now suppose B is discovered first. Then firm 2 produces B for sale in both countries at least until A is discovered. The outcome of the licensing game now depends, in part, on whether firm 2 can sell both A and B in country 1 when it buys a license for A. Because this would reduce firm 1's flow profit from its own market (compared to duopoly production of A in both countries), it is reasonable to assume that firm 1 will not sell a license unless firm 2 agrees to stop selling B in country 1. Hence, if firm 1 offers a license at fee L and firm 2 buys, then firm 1 earns $[\pi_1(A;A)/r] + L$ and firm 2 earns $[\pi_2(A;A)/r] - L$. Otherwise, B becomes the standard, so firm 1 earns $\pi_1^P(A;B)/r$ and firm 2 earns $\pi_2^P(B;A)/r$. Again, (A7) and (A8) are sufficient to ensure A is licensed if it is discovered second by firm 1.

Theorem 5. *Suppose country 2's government adopts the contingent standard policy and A is discovered by firm 1. Then, under (A1), (A2), (A3)', (A7), and (A8), there exist values $L_1 < 0$ and $L_2 > 0$ such that the unique SPE of the licensing subgame induced by this policy is firm 1 offers the license at fee L and firm 2 buys the license for any $L \in (L_1, L_2)$.*

The proof of Theorem 5 shows that country 2's government can choose a small, but positive, license fee such that licensing occurs if A is discovered by firm 1. Thus, whether A is discovered first or second, or by firm 1 or 2, it becomes the standard in country 2, ex post. As was the case with A as an arbitrary standard, this means that (a,a) is more likely to be the equilibrium in the c game than with no policy. In fact, in the c game (A2) is not sufficient to ensure that B is developed by firm j if A has been discovered. To allow that possibility, we make the stronger assumption

(A2)' $(\mu/r)\pi_j^1(B;A) > k_{jB}$ for $j = 1,2$

Even though this contingent standard makes doing R&D on B less attractive, it is still possible that (a,b) will be the equilibrium. Notice, however, that now there is an incentive for firm 2 to drop out of the race and wait to acquire a license for A.

Dropping out has the advantage of eliminating the uncertain flow costs of developing B, but also has the disadvantage of eliminating the possibility of earning monopoly profit with B.

<u>*Theorem 6*</u>: *Under (A1), (A2)′, (A3)′, (A7), and (A8), if (5) holds and* $k_{2A} - k_{2B} > \mu(F^c_{2A} - F^c_{2B})$*, then the unique SPE for all* $L \in (L_1, L_2)$ *is:*

(i) (a,b) *if* $k_{2B} < \mu\pi_2(B)/(r + \mu)$.

(ii) (a,d) *if* $k_{2B} > \mu\pi_2(B)/(r + \mu)$.

In the c game, firm 1's advantage in developing A does not ensure that firm 2 will develop B in equilibrium, as it did in the p game and in the absence of policy. Firm 2 will deviate from this outcome, to wait to license the patent for A, if the flow cost of doing R&D to discover B is greater than discounted expected monopoly profit with B. Several remarks about this are in order. First, it is possible that only A may be discovered under this policy even though both products would be discovered with no policy and with B as the standard. B never is discovered if A is discovered first. This must occur if firm 2 delays in equilibrium, but it can also occur if firm 2 tries to develop B. Second, if firm 2 does delay, then it is obviously giving up the chance of discovering B first and earning monopoly profit until discovery of A. Hence this indicates that delaying is more likely to be an equilibrium the lower the expected return from discovering B first. That is, delaying is more likely the smaller the flow profit from B and/or the larger the flow cost of discovering B. Delaying is also more likely the higher the return from acquiring the license, or the larger the duopoly profit from A and/or the smaller the license fee. Third, firm 1 is even willing to give a license to firm 2 (i.e., L = 0) because this ensures firm 1's product is adopted as a standard.

The remaining question of interest is whether the contingent policy is time consistent. The following theorem shows that if B as a standard increases flow welfare at the end of the game, the contingent standard policy is indeed time consistent.

<u>Theorem 7</u>. *Assume the conditions of Theorem 6 and $C_2(A,A) \geq C_2(A)$, where $C_2(A,A)$ is country 2's consumer surplus from duopoly production of A. If flow welfare in country 2 after both A and B are discovered is higher with B as the standard than in the absence of policy, then the contingent standard policy is time-consistent (i.e., expected welfare in country 2 at the beginning of the game, at the first discovery date, and at the end of the game are higher with this policy than with no policy).*

The intuition for this result is straightforward. If B is discovered first, then in the period before A is discovered flow welfare is the same with both policies as with no policy. Once A is discovered, whether it is first or second, then the contingent standard results in licensing. After this occurs, flow welfare is higher with the contingent standard than with B as a standard (which by hypothesis is higher than with no policy). Firm 2's flow profit must be higher because otherwise it would not buy a license. Consumers in country 2 are better off because consumer surplus from duopoly production of A exceeds that from monopoly production of A, and therefore that from monopoly production of B by (A4). Hence, the contingent standard is time consistent in the sense that it increases expected welfare, compared to that with no policy, at every date.

5. An Example

This section presents a simple market model to show that the results of Sections 3 and 4 are not vacuous. Assume the demand for good A in country j (j = 1,2) is $P_{jA} = D_j + \alpha - q_{jA} - q_{jB}$ and the demand for B in j is $P_{jB} = D_j - q_{jA} - q_{jB}$, where D_j and α are positive constants, q_{jA} is the output of A produced for sale in j, and q_{jB} is the output of B produced for sale in j. Assume the constant average cost of producing A or B is c, where $0 < \alpha < c < \min\{D_1,D_2\}$. Note α is a measure of the superiority of A. Also assume $\alpha < \min(D_1 - c, D_2 - c)$, so A is not superior enough that B cannot be produced when A is available.

If firm 1 develops A and firm 2 develops B, Nash equilibrium flow profits in the absence of policy (with quantities as strategies) are $\pi_1(A) = [(D_1 + \alpha - c)^2 + (D_2 + \alpha - c)^2]/4$, $\pi_1(A;B) = [(D_1 + 2\alpha - c)^2 + (D_2 + 2\alpha - c)^2]/9$, $\pi_2(B) = [(D_1 - c)^2 + (D_2 - c)^2]/4$, and $\pi_2(B;A) = [(D_1 - \alpha - c)^2 + (D_2 - \alpha - c)^2]/9$. Flow consumer surplus in country j is $C_j(A) = (D_j + \alpha - c)^2/8$, $C_j(B) = (D_j - c)^2/8$, and $C_j(A,B) = (2D_j + \alpha - 2c)^2/18$. In the p game, $\pi_1^p(A) = (D_1 + \alpha - c)^2/4$, $\pi_1^p(A;B) = (D_1 + 2\alpha - c)^2/9$, $\pi_2^p(B) = \pi_2(B)$, $\pi_2^p(B;A) = [(D_1 - \alpha - c)^2/9] + [(D_2 - c)^2/4]$, $C_1^p(A) = C_1(A)$, $C_1^p(B) = C_1(B)$, $C_1^p(A,B) = C_1(A,B)$, $C_2^p(A) = 0$, and $C_2^p(B) = C_2^p(A,B) = C_2(B)$. One can verify these satisfy (A1) and (A5)-(A6). Moreover, flow costs of R&D can always be chosen so that (a,b) is the equilibrium with B as the standard. Then ordinary algebra then gives the following.

<u>*Lemma*</u>.

(i) $W_2(F_{2B}) \gtreqless W_2(F_{2B}^p)$ *if and only if* $\alpha \lesseqgtr (D_2 - c)/2$.

(ii) If $\mu/r \le 3/2$, *then* $W_2(a,b) > W_2^p(a,b)$ *for all* α, *but if* $\mu/r \ge 3/2$, *then there exists a unique* α_W *such that* $W_2(a,b) \gtreqless W_2^p(a,b)$ *if and only if* $\alpha \gtreqless \alpha_W$, *where* α_W *is defined by* $3(D_2 + \alpha_W - c)^2 + 2(\mu/r)[4\alpha_W^2 - (D_2 - c)^2] = 0$ *and* $0 < \alpha_W < (D_2 - c)/2$.

(iii) If $\mu/r \le 3$, *then* $W_2(S_{2B}) > W_2(S_{2B}^p)$ *for all* α; *but if* $\mu/r > 3$, *then there exists a unique* α_S *such that* $W_2(S_{2B}) \gtreqless W_2(S_{2B}^p)$ *if and only if* $\alpha \gtreqless \alpha_S$, *where* α_S *is defined by* $3(D_2 + \alpha_S - c)^2 + (\mu/r)[4\alpha_S^2 - (D_2 - c)^2] = 0$ *and* $0 < \alpha_S < \alpha_W < (D_2 - c)/2$.

In this example, after both A and B are discovered, the gain to firm 2 from B as a standard exceeds the loss to consumers if and only if $\alpha < (D_2 - c)/2$. However, in order for the standard in the p game to increase expected welfare in all cases also requires that the hazard rate μ be large relative to the discount rate r. This additional condition is needed to insure that the future gains after both have been discovered are large enough to offset the expected loss to consumers if A is discovered first.

If licensing occurs in the c game, then firm 2's profit is $\pi_2(A;A) = [(D_1 + \alpha - c)^2 + (D_2 + \alpha - c)^2]/9$, and consumer surplus in country 2 is $C_2(A,A) = \frac{2}{9}(D_2 + \alpha - c)^2 > C_2(A)$. It then follows from Theorem 7 that the contingent standard improves welfare at all dates for any $\alpha < (D_2 - c)/2$ such that (A7) and (A8) hold (so that licensing occurs if A is discovered first). For this example, (A7) requires

$$[(D_1 + \alpha - c)^2 + (D_2 + \alpha - c)^2][(1.25r/\mu) - 1] < -(D_1 + 2\alpha - c)^2,$$

and (A8) requires

$$(D_1 + \alpha - c)^2 + (D_2 + \alpha - c)^2 > (D_1 - \alpha - c)^2 + 2.25(D_2 - c)^2.$$

It is straightforward to show that these conditions and $\alpha < (D_2 - c)/2$ can hold simultaneously (for example, set $D_2 = 12$, $D_1 = 10$, $\alpha = 4$, and $c = 2$).

6. Conclusion

This paper has examined anticipatory product standards in an international setting where one government imposes a domestic standard to alter the competitive position of its firm in an R&D race. As we noted earlier, governments often impose standards for precisely this reason. Public policy debates on the efficacy of such standards have focused on such issues as whether standards should be announced before products are developed, whether they indeed alter the relative positions of domestic and foreign firms in races, and whether consumer losses from standards outweigh any benefits to domestic firms. Our work shows that the answers to these questions depend crucially on the way standards are defined, as well as the underlying R&D competition.

We addressed these questions in the context of a patent race between a domestic and a foreign firm, where the foreign firm has an advantage in developing the superior of two closely related products. Firms choose whether to race to develop a single product, develop different products, or drop out of the race. In the absence of a standard, the foreign firm will do R&D on the superior product and the domestic firm will race to develop an imperfect substitute if the foreign firm's advantage is large enough.

Our results show that a standard may or may not alter firms' equilibrium strategies. An important point to come out of the analysis is that simple anticipatory standards can be problematic even when they do not change the equilibrium. Because discovery dates are uncertain, a simple standard imposed before the successful completion of R&D may decrease expected welfare even if it is certain to improve flow welfare at the end of the race. This is because the standard benefits the domestic firm only after its R&D has succeeded, but consumers suffer losses once the foreign firm succeeds. Thus a standard can be time inconsistent if the foreign firm discovers its product before the domestic firm is successful. For this reason, contingent policies such as the one considered in the c game can be Pareto superior because they allow consumers and firms to benefit regardless of which product is discovered first.

Notice that both the simple and contingent standards make it more likely that firms will race to develop the product favored by the standard. In this regard, our analysis shows that standards may indeed result in firms dropping out of the race. Although the time consistent standard examined here benefits the domestic firm, it does so because licensing is possible, so that if the firm has a large enough cost disadvantage it will drop out of the race. Finally, notice that we did not make welfare comparisons for cases in which a standard would alter the equilibrium.

Such comparisons could be made, however, it would not be surprising to find that time consistent policies were even more complicated in those cases.

Footnotes

[1]See David and Greenstein (1990) for an excellent survey of needed research on the use of standards in dynamic environments.

[2]See also p. 33 and pp. 205-210 on the Task Force's recommendation that government policy be aimed at "restoring" the consumer electronics industry.

[3]The share of foreign companies in U.S. patent registrations rose from 35% in 1975 to 47% in 1988 (U.S. Department of Commerce, 1990). See McCulloch (1988) for an analysis of U.S. high technology exports.

[4]This particular case involved a switch in the standard from the CBS system that was not retrocompatible to the NTSC retrocompatible system developed by other domestic firms. See Hazard and Daems (1988).

[5]See Farrell and Shapiro (1991) on licensing requirements associated with standard setting of HDTV.

[6]Mayer (1982) examines a theoretical model of the protective effect of standards, but his analysis is not strategic and he abstracts from issues of compatibility and innovation.

[7]Delaying can be an equilibrium in certain policy scenarios, such as that considered in Section 4. It can also be an equilibrium when there are spillovers or if imitation is possible. It is also possible for (a,b) to be an equilibrium with spillovers (or imitation) because a firm earns monopoly profits for some period if it discovers its product first. Results for the race with spillovers are available from the authors.

[8]In the case of HDTV, some analysts predict that Japanese and European markets will grow faster than the U.S. market. Hence the Japanese may not find it worthwhile to modify their development strategy.

[9]If B as a standard reduces welfare after both products are discovered, it is not a credible policy for country 2's government. This lack of credibility alters the expected returns to firms 1 and 2 so that licensing will not occur in equilibrium. Thus the benefits associated with licensing under the contingent policy we consider would not occur.

[10](A7) and (A8) are stronger than is necessary for licensing to occur. All that is necessary is that $F_{1A}^{c} > F_{1A}^{n}$ and $S_{2B}^{c} > S_{2B}^{n}$. A natural sufficient condition (which is also weaker than (A7) and (A8)) is that the present value of both firms' profits under licensing exceeds the present value of both firms' expected profits without licensing,

$$[\pi_1(A;A) + \pi_2(A;A)]/r > [\pi_1(A) + (\mu/r)[\pi_1^p(A;B) + \pi_2^p(B;A)]]/(r + \mu).$$

We make the stronger assumptions because they guarantee the contingent standard is time consistent under natural rankings of consumer surplus.

References

Bagwell, K. and Staiger, R., "The Sensitivity of Strategic R&D Policy to Market Conditions," mimeo, Stanford University, 1989.

Beath, J., "Models of Technological Competition for the Analysis of Intellectual Property Rights and the Uruguay Round," mimeo, 1990.

Besen, S.M. and Saloner, G., "The Economics of Telecommunications Standards," in R. Crandall and K. Flamm, eds., Changing the Rules: Technological Change, International Competition, and Regulation in Telecommunications, Washington: The Brookings Institution, 1989.

Crane, R.J., The Politics of International Standards, Norwood, New Jersey: Ablex Publishing, 1979.

David, P., "Some New Standards for the Economics of Standardization in the Information Age," in P. Dasgupta and P. Stoneman, eds., Economic Policy and Technological Performance, Cambridge, England: Cambridge University Press, 1987.

David, P. and Greenstein, S., "The Economics of Compatibility Standards: An Introduction to Recent Research," The Economics of Innovation and New Technology I, 1990, 3-41.

Dixit, A., "A General Model of R&D Competition and Policy," RAND Journal of Economics 19, 1988a, 317-326.

__________, "International R&D Competition and Policy," in A. M. Spence and H. A. Hazard (ed.), International Competitiveness, Cambridge: Ballinger, 1988b.

Farrell, J. and G. Saloner, "Standardization, Compatibility, and Innovation," RAND Journal of Economics 16, 1985, 70-83.

__________, "Installed Base and Compatibility: Innovation, Product Preannouncements, and Predation," American Economic Review 76, 1986a, 940-955.

__________, "Standardization and Variety," Economic Letters 20, 1986b, 71-74.

__________, "Coordination Through Committees and Markets," RAND Journal of Economics 19, 1988, 235-251.

Farrell, J. and C. Shapiro, "Strategy and Standards in High-Definition Television," mimeo, University of California at Berkeley, June 1991.

Fudenberg, D., R. Gilbert, J. Stiglitz, and J. Tirole, "Preemption, Leapfrogging, and Competition in Patent Races," European Economic Review 22, 1983, 3-31.

Gilbert, R. and D. Newbery, "Preemptive Patenting and the Persistence of Monopoly," American Economic Review 72, 1982, 514-526.

Hazard, H. and H. Daems, "Technical Standards and Competitive Advantage in World Trade," mimeo, Harvard University, 1988.

Katz, M. and C. Shapiro, "Network Externalities, Competition, and Compatibility," American Economic Review 75, 1985, 424-440.

__________, "Technology Adoption in the Presence of Network Externalities," Journal of Political Economy 94, 1986a, 822-841.

__________, "Product Compatibility Choice in a Market with Technological Progress," Oxford Economic Papers: Special Issue on Industrial Organization, 1986b.

Krishna, K., "High-Tech Trade Policy," in R. Baldwin, C. Hamilton, and A. Sapir (ed.), US-EC Trade Relations, Chicago: University of Chicago Press, 1988.

Lecraw, D. J., "Japanese Standards: A Barrier to Trade?" in H. Landis Gabel, ed., Product Standardization and Competitive Strategy, Elsevier Science Publishers, 1987.

Lippman, S. and K. McCardle, "Preemption in R&D Races," European Economic Review 32, 1988, 1661-1669.

Mayer, W., "The Tariff Equivalent of Import Standards," International Economic Review 23, 1982, 723-734.

McCulloch, R., "The Challenge to U.S. Leadership in High-Technology Industries (Can the United States Maintain Its Lead? Should It Try?," NBER Working Paper #2513, 1988.

Pelkmans, J. and R. Beuter, "Standardization and Competitiveness: Private and Public Strategies in the EC Color TV Industry," in H. Landis Gabel, ed., Product Standardization and Competitive Strategy, Elsevier Science Publishers, 1987.

President's Commission on Industrial Competitiveness, Global Competition: The New Reality, Washington, D.C.: U.S. Government Printing Office, 1986.

Reinganum, J., "The Timing of Innovation: Research, Development, and Diffusion," in R. Schmalensee (ed.), The Handbook of Industrial Organization, Amsterdam: North Holland, 1989.

Shaked, A. and J. Sutton, "Relaxing Price Competition Through Product Differentiation," Review of Economic Studies 49, 1982, 3-13.

Sims, C., "HDTV: Will the U.S. Be in the Picture," New York Times, September 27, 1988, 27.

Staiger, R. and Q. Tabellini, "Discretionary Trade Policy and Excessive Protection," American Economic Review 77, 1987, 823-837.

Technology Task Policy Force, Report of the Committee on Science, Space, and Technology, Washington, D.C.: U.S. House of Representatives, 1988.

Wysocki, B., "Technology: The Final Frontier," Wall Street Journal, November 14, 1988, Section 4.

Yanagawa, N., "Network Externalities and Trade Policies," mimeo, University of Tokyo, 1990.

Table 1

Payoffs to Firm 1

Payoffs to firm 1 if firm 2's strategy is to do nothing until after discovery of A or B by firm 1

$$P_1(a,d) = (\mu F_{1A} - k_{1A})/(r + \mu)$$

$$P_1(b,d) = (\mu F_{1B} - k_{1B})/(r + \mu)$$

$$P_1(d,d) = 0$$

Payoffs to firm 1 if firm 2's strategy is to do R&D on B

$$P_1(a,b) = (\mu F_{1A} + \mu S_{1A} - k_{1A})/(r + 2\mu)$$

$$P_1(b,b) = (\mu F_{1B} + \mu S_{1A} - k_{1B})/(r + 2\mu)$$

$$P_1(d,b) = \mu S_{1A}/(r + \mu)$$

Payoffs to firm 1 if firm 2's strategy is to do R&D on A

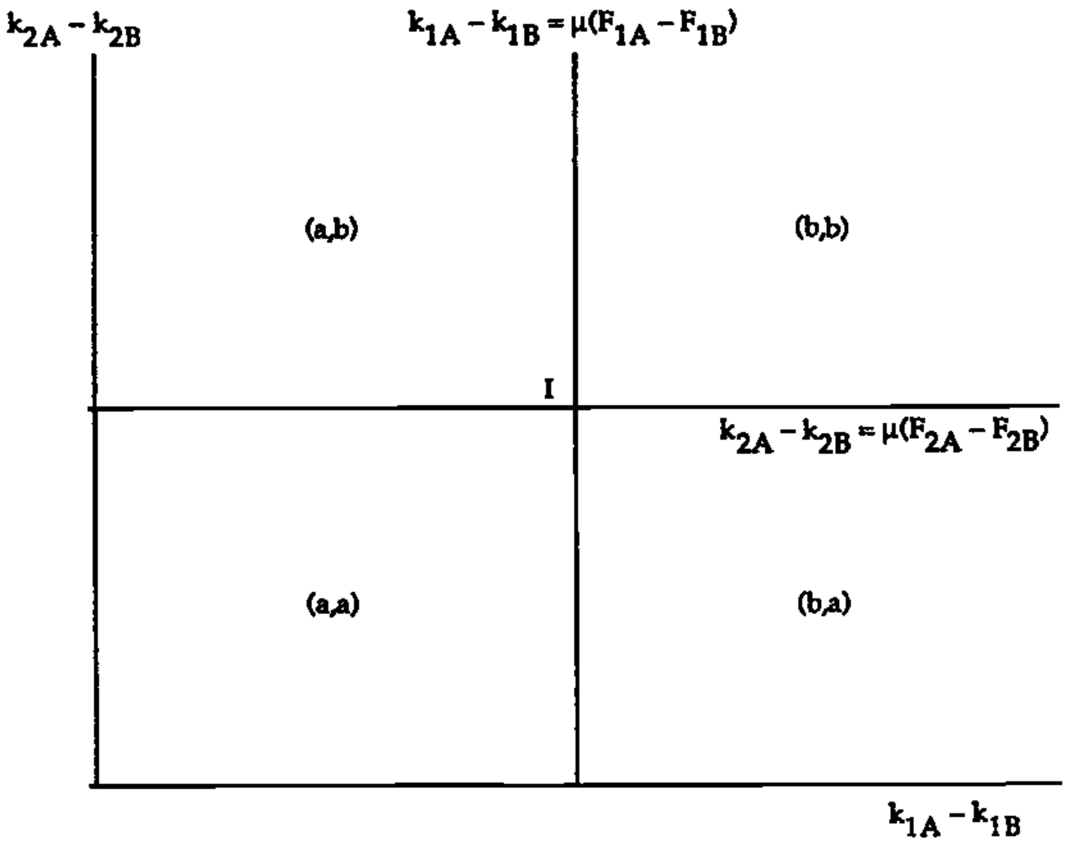
$$P_1(a,a) = (\mu F_{1A} + \mu S_{1B} - k_{1A})/(r + 2\mu)$$

$$P_1(b,a) = (\mu F_{1B} + \mu S_{1B} - k_{1B})/(r + 2\mu)$$

$$P_1(d,a) = \mu S_{1B}/(r + \mu)$$

$P_1(s_1,s_2)$ is the expected payoff to firm 1 (discounted to $t = 0$) if firm 1 uses s_1 and firm 2 uses s_2, $s_i \in \{a,b,d\}$.

Figure 1



Appendix

Proof of Theorem 1. From Table 1:

$$P_1(a,a) - P_1(b,a) = P_1(a,b) - P_1(b,b) = [(\mu F_{1A} - k_{1A}) - (\mu F_{1B} - k_{1B})]/(r + 2\mu) \text{ and}$$

$$P_1(a,d) - P_1(b,d) = [\mu(F_{1A} - F_{1B}) - (k_{1A} - k_{1B})]/(r + \mu).$$

From the analogous payoffs to firm 2,

$$P_2(a,a) - P_2(a,b) = P_2(b,a) - P_2(b,b) = [(\mu F_{2A} - k_{2A}) - (\mu F_{2B} - k_{2B})]/(r + 2\mu) \text{ and}$$

$$P_2(d,a) - P_2(d,b) = [\mu(F_{2A} - F_{2B}) - (k_{2A} - k_{2B})]/(r + \mu).$$

These facts prove the "only if" parts of (i)-(iv).

Now observe that (A1)-(A3) imply $P_1(a,b) > P_1(d,b)$, $P_1(a,d) > P_1(d,d)$, $P_1(b,a) > P_1(d,a)$, $P_1(b,d) > P_1(d,d)$, $P_2(b,a) > P_2(b,d)$, $P_2(d,a) > P_2(d,d)$, $P_2(a,b) > P_2(a,d)$, and $P_2(d,b) > P_2(d,d)$.

Suppose that $\mu(F_{1A} - F_{1B}) > k_{1A} - k_{1B}$. Then $P_1(a,s_2) > P_1(b,s_2)$ for all $s_2 \in \{a,b,d\}$. This plus $P_1(b,a) > P_1(d,a)$ implies $P_1(a,a) > P_1(d,a)$, and so $P_1(a,s_2) > P_1(d,s_2)$ for all $s_2 \in \{a,b,d\}$ also. That is, a is firm 1's strongly dominant strategy if $\mu(F_{1A} - F_{1B}) > k_{1A} - k_{1B}$. Now suppose instead that $\mu(F_{1A} - F_{1B}) < k_{1A} - k_{1B}$. Then $P_1(b,s_2) > P_1(a,s_2)$ for all $s_2 \in \{a,b,d\}$. This plus $P_1(a,b) > P_1(d,b)$ implies $P_1(b,b) > P_1(d,b)$, and so $P_1(b,s_2) > P_1(d,s_2)$ for all $s_2 \in \{a,b,d\}$. Hence, b is firm 1's strongly dominant strategy if $\mu(F_{1A} - F_{1B}) < k_{1A} - k_{1B}$. Analogous arguments show firm 2's strongly dominant strategy is a if $\mu(F_{2A} - F_{2B}) > k_{2A} - k_{2B}$, and b if $\mu(F_{2A} - F_{2B}) < k_{2A} - k_{2B}$. These results prove the "if" parts of (i)-(iv), and (v) then follows immediately.

Proof of Theorem 2. The proof of (i) and (ii) are entirely analogous to that in Theorem 1. Note F^P_{iA} and F^P_{iB} are computed as in (2) and (4) with $\pi^P_i(A)$, $\pi^P_i(A;B)$, $\pi^P_i(B)$, and $\pi^P_i(B;A)$ replacing $\pi_i(A)$, $\pi_i(A;B)$, $\pi_i(B)$, and $\pi_i(B;A)$. It then follows that $F^P_{iA} - F^P_{iB} < F_{iA} - F_{iB}$ for $i = 1,2$, so it is possible that both $\mu(F^P_{1A} - F^P_{1B}) < k_{1A} - k_{1B}$

$< \mu(F_{1A} - F_{1B})$ and $k_{2A} - k_{2B} > \mu(F_{2A} - F_{2B}) > \mu(F^p_{1A} - F^p_{1B})$. If so, then (a,b) is the unique SPE without the standard, but (b,b) is the SPE with the standard.

Proof of Theorem 3. If $W_1(F^p_{1A})$, $W_1(S^p_{1A})$, $W_2(F^p_{2B})$, and $W_2(S^p_{2B})$ are the expressions for expected welfare at the first discovery date under the standard, then these are defined by (6)-(9) with $\pi^p_i(\bullet)$ and $C^p_i(\bullet)$ replacing $\pi_i(\bullet)$ and $C_i(\bullet)$. Similarly, let $W^p_1(a,b)$ and $W^p_2(a,b)$ be initial expected welfare under the standard. Then these are defined by (10) and (11) with $W_1(F^p_{1A})$, $W_1(S^p_{1A})$, $W_2(F^p_{2B})$, and $W_2(S^p_{2B})$ replacing $W_1(F_{1A})$, $W_1(S_{1A})$, $W_2(F_{2B})$, and $W_2(S_{2B})$. One can show that $W_2(F_{2B}) - W_2(F^p_{2B}) = (\mu/r)[\pi_2(B;A) - \pi^p_2(B;A) + C_2(A,B) - C^p_2(A,B)]/(r + \mu)$ and $W_2(S_{2B}) - W_2(S^p_{2B}) = \{C_2(A) + (\mu/r)[\pi_2(B;A) - \pi^p_2(B;A) + C_2(A,B) - C^p_2(A,B)]\}/(r + \mu)$. After both A and B are discovered, country 2's flow welfare is $\pi^p_2(B;A) + C^p_2(A,B)$ with the standard and $\pi_2(B;A) + C_2(A,B)$ without it, so it reduces flow welfare if and only if $\pi_2(B;A) - \pi^p_2(B;A) + C_2(A,B) - C^p_2(A,B) > 0$. Hence, $W_2(F_{2B}) > W_2(F^p_{2B})$ and $W_2(S_{2B}) > W_2(S^p_{2B})$, whence $W_2(a,b) > W^p_2(a,b)$.

Proof of Theorem 4. From the proof of Theorem 3, if flow welfare is higher with the standard after both are discovered, $\pi_2(B;A) - \pi^p_2(B;A) + C_2(A,B) - C^p_2(A,B) < 0$, then $W_2(F^p_{2B}) > W_2(F_{2B})$. However, note that $C_2(A) > 0$ implies $W_2(S_{2B}) > W_2(S^p_{2B})$ can hold. Further, because $W_2(a,b) - W^p_2(a,b) = \mu[W_2(F_{2B}) - W_2(F^p_{2B}) + W_2(S_{2B}) - W_2(S^p_{2B})]/(r + 2\mu)$, it is possible that $W_2(F^p_{2B}) > W_2(F_{2B})$, $W_2(S_{2B}) > W_2(S^p_{2B})$, and either $W^p_2(a,b) > W_2(a,b)$ or $W_2(a,b) > W^p_2(a,b)$.

Proof of Theorem 5. Firm 2's strongly dominant strategy is to buy a license if $S^c_{2B} > S^n_{2B}$ (when A is discovered first) and $[\pi_2(A;A)/r] - L > \pi^p_2(B;A)/r$ (when B is discovered first). It is easily shown that $[\pi_2(A;A)/r] - L > \pi^p_2(B;A)/r$ implies

$S^c_{2B} > S^n_{2B}$. Hence, whether A is discovered first or second, firm 2's strongly dominant strategy is to buy if $[\pi_2(A;A)/r] - L > \pi^p_2(B;A)/r$, or

$$L < L_2 = [\pi_2(A;A) - \pi^p_2(B;A)]/r,$$

where (A1) and (A8) imply $L_2 > 0$. Therefore, given any compulsory fee $L < L_2$, firm 1's strongly dominant strategy is to offer to sell a license at L if $F^c_{1A} > F^n_{1A}$ (when A is discovered first) and $[\pi_1(A;A)/r] + L > \pi^p_1(A;B)/r$ (when B is discovered first). Because $F^c_{1A} > F^n_{1A}$ implies $[\pi_1(A;A)/r] + L > \pi^p_1(A;B)/r$, whether A is discovered first or second, firm 1's strongly dominant strategy is to offer to sell for any $L < L_2$ if $F^c_{1A} > F^n_{1A}$. One can show that $F^c_{1A} > F^n_{1A}$ if and only if

$$L > L_1 = [(\pi_1(A) + (\mu/r)\pi^p_1(A;B))/(r + \mu)] - [\pi_1(A;A)/r],$$

where (A1) and (A7) imply $L_1 < 0$. Thus, whether A is discovered first or second, the unique SPE of this licensing game is firm 1 offers to sell and firm 2 buys for all $L \in (L_1, L_2)$.

Proof of Theorem 6. Under the contingent policy,

$$P^c_1(a,a) - P^c_1(b,a) = P^c_1(a,b) - P^c_1(b,b) = [F^c_{1A} - F^c_{1B} - (k_{1A} - k_{1B})]/(r + 2\mu),$$
$$P^c_1(a,d) - P^c_1(b,d) = [F^c_{1A} - F^c_{1B} - (k_{1A} - k_{1B})]/(r + \mu),$$
$$P^c_2(a,a) - P^c_2(a,b) = P^c_2(b,a) - P^c_2(b,b) = [F^c_{2A} - F^c_{2B} - (k_{2A} - k_{2B})]/(r + 2\mu), \text{ and}$$
$$P^c_2(d,a) - P^c_2(d,b) = [F^c_{2A} - F^c_{2B} - (k_{2A} - k_{2B})]/(r + \mu).$$

Because $F^c_{1A} > F^p_{1A}$ and $F^c_{1B} < F^p_{1B}$, it follows that $k_{1A} - k_{1B} < \mu(F^p_{1A} - F^p_{1B})$ implies $k_{1A} - k_{1B} < \mu(F^c_{1A} - F^c_{1B})$. Moreover, (A1), (A2)′, and (A3)′ imply $P^c_1(a,b) > P^c_1(d,b)$, $P^c_1(a,d) > P^c_1(d,d)$, and $P^c_1(b,a) > P^c_1(d,a)$. Hence, if (21) holds, then developing A is firm 1's strongly dominant strategy because $P^c_1(a,s_2) > P^c_1(b,s_2)$ and $P^c_1(a,s_2) > P^c_1(d,s_2)$ for $s_2 \in \{a,b,d\}$. Because $k_{2A} - k_{2B} > \mu(F^c_{2A} - F^c_{2B})$ implies $P^c_2(a,b) > P^c_2(a,a)$, the SPE must have firm 1 developing A and firm 2 either developing B, delaying, or randomizing on these two pure strategies. The result follows from the fact that $P^c_2(a,b) \gtreqless P^c_2(a,d)$ if and only if $\mu\pi_2(B)/(r + \mu) \gtreqless k_{2B}$. Moreover, if $\pi_2(B) \le$

$(r + \mu)\pi_2^1(B;A)/\mu$, then $k_{2B} \geq \mu\pi_2(B)/(r + \mu)$ and (A2)′ can hold simultaneously, so (ii) can occur.

Proof of Theorem 7. Under these assumptions, (a,b) is the unique SPE in the p game and the game with no policy, while in the c game the unique SPE is (a,b) if $k_{2B} < \mu\pi_2(B)/(r + \mu)$ and (a,d) if $k_{2B} > \mu\pi_2(B)/(r + \mu)$. First suppose $k_{2B} < \mu\pi_2(B)/(r + \mu)$. Then $W_2^c(a,b) - W_2(a,b) = \mu[W_2(F_{2B}^c) - W_2(F_{2B}) + W_2(S_{2B}^c) - W_2(S_{2B})]/(r + 2\mu)$. One can show $W_2(F_{2B}^c) > W_2(F_{2B})$ if and only if $L < L^w$, where

$$L^w = [\pi_2(A;A) - \pi_2(B;A) + C_2(A,A) - C_2(A,B)]/r.$$

Similarly, $W_2(S_{2B}^c) > W_2(S_{2B})$ if and only if $L < L^{wb}$, where

$$L^{wb} = [\pi_2(A;A)/r] - [\{(\mu/r)\pi_2(B;A) - k_{2B}\}/(r + \mu)] + [C_2(A,A)/r] - [\{C_2(A) + (\mu/r)C_2(A,B)\}/(r + \mu)].$$

One can show that (A4), $\pi_2^p(B;A) + C_2^p(A,B) > \pi_2(B;A) + C_2(A,B)$, and $C_2(A,A) \geq C_2(A)$ imply both $L^w > L_2$ and $L^{wb} > L_2$, so $W_2(F_{2B}^c) > W_2(F_{2B})$, $W_2(S_{2B}^c) > W_2(S_{2B})$, and thus $W_2^c(a,b) > W_2(a,b)$.

Now suppose $k_{2B} > \mu\pi_2(B)/(r + \mu)$ so $W_2^c(a,d) = \mu W_2(S_{2B}^c)/(r + \mu)$. One can show $W_2^c(a,d) > W_2(a,b)$ if and only if $L < L^{wd}$, where

$$L^{wd} = [\{\pi_2(A;A) + C_2(A,A)\}/r] - [\{\pi_2(B) + C_2(B) + 2(\mu/r)[\pi_2(A;B) + C_2(A,B)]\}/(r + 2\mu)] + [k_{2B}/\mu].$$

Because (A4), $\pi_2^p(B;A) + C_2^p(A,B) > \pi_2(B;A) + C_2(A,B)$, $C_2(A,A) \geq C_2(A)$, and $k_{2B} > \mu\pi_2(B)/(r + \mu)$ imply $L^{wd} > L_2$, we have $W_2^c(a,d) > W_2(a,b)$ also.