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STANDARDIZATION, COMPATIBILITY AND INNOVATION

by Joseph Farrell*
and
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M.I.T. Working Paper #345
April, 1984

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1. Introduction

Many goods are "compatible" or "standardized", in the sense that different manufacturers provide more interchangablility than is logically necessary. For instance, CBS and NBC television can be received on the same set; GTE Telephone subscribers can talk to AT&T subscribers; some - though far from all - computer programs written for one computer can be run on another; different manufacturers' nuts and bolts can be used together; and there are fewer types of sparkplug than there are models of automobile.[1]

It is clear that, other things being equal, there are important benefits of such standardization. That is presumably why government smiles on the development of such standards, for instance through the National Bureau of Standards, the British Standards Institute, etc.[2] Consumers benefit in a number of ways. There may be a direct "network externality", in the sense that one consumer's value for a good increases when another consumer has a compatible good, as in the case of telephones, or as when friends want to be able to exchange software for their personal computers. There may be a market-mediated effect, as when a complementary good (spare parts, servicing, software...) becomes cheaper and more readily available the greater the extent of the (compatible) market. There may be a benefit to having a thicker second-hand (used) market. Finally, compatibility may enhance price competition among sellers.

All these except the last will feed back into producers' incentives, giving them some incentive to make their products compatible. In addition, some kinds of standardization will allow producers to get inputs more cheaply by expoloiting economies of scale in the production of those inputs. In fact, most standardization is voluntary, rather than government-imposed, and comes about because of these "network externalities" among producers: other things being equal, a producer will often prefer to make his product compatible with his rivals'. However, this incentive does not necessarily correspond exactly to social benefits.

Katz and Shapiro (1983) develop a duopoly model in which consumers value a product more highly when it is "compatible" with other consumers' products. They call this effect "network externalities". In this framework they analyze the social and private incentives for firms to produce compatible products or to switch from incompatible to compatible products. They find, for example, that a dominant firm may choose to remain incompatible with a rival because it will suffer a substantial decline in market share if it becomes compatible, thereby increasing the value to consumers of its rival's product.

Although standardization has important social benefits, as outlined above, it may have important social costs as well. Apart from the reduction in variety, which is unfortunate if different buyers would prefer different types of product, there is another possible cost, less well accounted for in the market, which is the subject of this paper. Intuitively, it is plausible that the industry, once firmly bound together by the benefits of compatibility or standardization, will be inclined to move too reluctantly to a new, better, standard, because of the coordination problems involved. For example, Hemenway (1975) reports that the National Bureau of Standards declined to write interface standards for the computer industry because it feared that such standards would retard innovation. And many investigators believe that the standard "QWERTY" typewriter keyboard is inferior to alternatives such as the Dvorak, even allowing for retraining costs: the reason for its persistence is (supposedly) the overwhelming benefit from compatibility. It is this possible "excess inertia" impeding the collective switch from a common standard or technology to a new standard or technology that is the topic of this paper.

In a simple model where it is common knowledge that the firms are identical, and where they decide sequentially whether to change to the new technology, a somewhat surprising result emerges: if all firms favor the change then all <u>will</u> change! In other words, there is no excess inertia impeding the change. However, both unanimity and complete information are necessary for this result.

Once we allow for incomplete information about the "eagerness" of each firm to switch to the new technology, the equilibria that arise resemble bandwagons. Firms that are strongly in favor of the change switch early, while those only moderately in favor wait to see if others will switch and then join the bandwagon if it in fact gets rolling. If that happens, some who are against the change will end up joining in. Among those that initiate the bandwagon are firms who will regret switching if in fact they are not followed. However they are sufficiently in favor of the change to be willing to take that risk; the compensating benefit is the hope that they will precipitate the bandwagon effect.

We show that in this model with incomplete information there is always excess inertia. Two types of excess inertia occur. In the first, and the most striking, (symmetric inertia), the firms are unanimous in their preference for the new technology and yet the change is not made. This arises when the firms are all only moderately in favor of the change, and hence are insufficiently motivated to start the bandwagon rolling themselves although they would jump on it if it did get rolling. As a result they end up with the <u>status quo</u>. In the second type of inertia ("asymmetric inertia") the firms differ in their preferences over technologies but the total benefits from the switch exceed the total costs. As before this inertia arises because those in favor are insufficiently in favor to start the ball rolling.

Symmetric inertia is purely a problem of coordination. Hence one might expect that, as in Farrell (1982), non-binding communication of preferences and intentions may remove the inertia. However we show that while this indeed extinguishes the symmetric excess inertia, it exacerbates the problem of asymmetric inertia.

In the above models, the strategic actions of firms are limited to attempting to influence whether the bandwagon gets rolling. However, one might also expect firms to try to manipulate market structure by taking actions that drive rivals out of the industry. Since it is costly to change to the new technology, a "follower" firm may be reluctant to follow a dominant firm to the new technology. If, in addition, the follower's costs are sufficiently increased (or profits reduced) when its technology becomes incompatible with the dominant firm's, it may prefer leaving the industry to remaining alone with the old technology. By changing technologies, therefore, the dominant firm may eliminate a rival and the resulting increase in concentration may be sufficient to compensate it for the increase in its own costs, and the costs of switching to the new technology. We provide an example in which this occurs in equilibrium.

The paper is organized as follows: the model with complete information is analyzed in Section II, incomplete information is introduced in Section III, and communication in that model is discussed in Section IV. Section V presents the model with manipulative technology change. Section VI concludes and suggests avenues for future research.

II. A Model with Sequential Decisions and Complete Information.

One of the clearest features of noncooperative[3] standard setting is its bandwagon quality. When compatibility is an important consideration for a firm setting its product specifications, early movers have the ability to influence later movers' decisions: if firm 1 switches to a new standard, then firm 2 will find switching more attactive than if firm 1 had not switched. In this section, we present a simple model of that effect in which firms' decisions are taken sequentially, and payoffs are common knowledge. We show that if, allowing for transition costs, all firms would prefer the industry to switch, then the only perfect equilibrium is that they all do so.

First, we define some notation.

Let $N = \{1, 2, \ldots, N\}$ denote the set of firms in the industry. For any $j \varepsilon N$ and any $S \subseteq N$ containing j, we define $B_j(S, Y)$ as the net benefit to firm j from switching, together with the other firms in S, from the old standard (X) to the new one (Y), relative to the benefit if all firms stick with X. In other words, we normalize so that each firm gets zero benefit in the status quo, and then $B_j(S, Y)$ is the value to j of switching and having the other members of S switch. This is a present value, and net of any transition costs. Thus, firm j would be in favor of a change by the entire industry if and only if $B_j(N, Y) > 0$

We also define $B_j(S, X)$ for subsets S containing j, as j's payoff if j and the other members of S stay with X, while the members of N-S switch to Y. Thus in particular $B_j(N, X) = 0$ by normalization.

The basic <u>assumption of positive network externalities</u> can now be phrased as:

(A1): If $j \in S \subseteq S'$ and $k = X$ or Y then:

$$B_j(S, k) \leq B_j(S', k)$$

This says that, whatever j's choice, he prefers to have more others make the same choice. This introduces the coordination considerations which are the focus of the paper.

Symmetric case. In some of the work below, we assume that $B_j(S, X)$ depends only on the number of firms in S, and likewise for $B_j(S, Y)$. Thus we can write the benefit functions as $B_j(m, k)$, where m is the total number of firms in S, i.e., the number making the choice that j makes. Moreover, we will sometimes assume that the function $B_j(\cdot, \cdot)$ is the same for all j, so we can simply write $B(m, X)$ or $B(m, Y)$. (In Section III, we allow $B(\cdot,\cdot)$ to differ among firms, but we think of it as a function of type (i) rather than index number (j), and write it as $B^i(\cdot,\cdot)$).

The Model. The set N of firms is given, as are the alternative standards X and Y. All firms are initially at standard X. There are n periods to the game, which has perfect and complete information. In period j, firm j decides whether or not to switch to Y. If S denotes the set of firms who do switch, then the payoffs are

$$B_j(S, Y) \text{ for } j \in S$$

$$B_j(N \backslash S, X) \text{ for } j \notin S$$

Proposition 1:

Suppose that, for each j,

$$B_j(N, Y) > B_j(\{j, j+1, \ldots, N\}, X). \tag{2.1}$$

Then the unique perfect equilibrium involves all firms switching.

Proof: The condition (2.1) ensures that, for each j, if 1,...,j-1 have already switched, then j prefers to switch (if he believes all the rest would follow) rather than to stay (whatever his beliefs about how many others would switch). Since j knows this is true for j+1,...,n, he knows they will switch if he does; and so he will switch.

Corollary: If $B_j(N, Y) > B_j(N, X)$ for all j, (2.2)

then the unique perfect equilibrium involves all firms switching. Therefore, in this model, there can be no excess inertia in the symmetric sense that each agent prefers an overall industry switch but it fails to happen.

However, (2.1) is weaker than unanimity (2.2). So Proposition 1 tells us that players late in the game sometimes switch even though $B_j(N, Y) < B_j(N, X)$. Moreover, it is clear that there is no necessary relationship between $\sum_j [B_j(N, Y) - B_j(N, X)]$ and the outcome of the game: we can get "excess inertia" or its opposite if we make judgements based on adding benefits.

Being late in the game is a strategic disadvantage because of our assumption that each agent gets only one chance to choose his standard; thus, early movers get to commit. In a game of complete information, there is no countervailing value to waiting to see how things turn out. This is expressed by the following result:

Proposition 2: Given the preferences of all agents, each agent is better-off (not necessarily strictly) moving earlier than moving later.[5]

Proposition 2 is proved in the Appendix. The essence of the proof is that having an earlier position gives power over later movers, and hence even earlier movers are obliged to treat one's preferences with more respect.

Intuitively, there is a benefit of commitment from moving early. In a general game, there can be a countervailing factor of "regret": once a Stackelberg follower has moved the leader would like to change his move, if he could. In this game, that does not happen: every sequential equilibrium would also be an equilibrium if firms decided simultaneously on their choices. The other factor which sometimes makes it desirable to move later in some other games, i.e. the fact that information may flow in, is also absent from this model, but is addressed in Section III.

A simple example in which Proposition 2 holds strictly is provided by the following two-firm case:

Firm A

	$B_A(m, X)$	$B_A(m, Y)$
m=1	-2	-1
m=2	0	1

Firm B

	$B_B(m, X)$	$B_B(m, Y)$
m=1	-2	-3
m=2	0	-1

If A goes first, the he will switch and B will follow. If B goes first, however, he will not switch, and A will then not switch. It is easy to check the claim of Proposition 2: that each firm prefers the outcome that results from its going first.

Endogenous Timing and a Bias for Switching

Hitherto, we have had no essential difference between X and Y, once switching costs were netted out from the benefits of Y. Each firm in turn could commit itself to X or to Y. We now discuss what will happen if a choice of Y is irreversible, while a choice "remain at X" is not. One reason this might be true is that remaining at X means a continuing and gradual replacement of plant, worker skills, etc., while a switch to Y, or a re-switch back to X, would involve a much greater cost. If this switching cost is substantial, a switch to Y will be seen as at least somewhat of a commitment, while remaining at X enables a firm to keep its options open. With this assumption, we can remove the artificial assumption that firms take their decisions in a pre-specified order. Instead, those who wish to choose Y go first, in effect. In view of Proposition 2, this will bias the outcome towards Y, in the sense that, among the specified-order equilibria, it is the most inclined to Y which will occur:

Proposition 3: Consider the set of equilibria of the game with different predetermined orders of move. Let S^* be the set of all firms who switch in some equilibrium.[7] When the game is played with endogenous timing and Y is a commitment but X is not, then all firms in S^* switch.

The proof of proposition 3 is in the Appendix.

Notice that proposition 3 implies that, with this form of endogenous timing, if all firms favor a switch ($B_j(N,Y) > 0$ for all j) then they will all switch. If no firm favors a switch, none will switch. But in intermediate cases, there is a bias for switching.

III. A Model With Incomplete Information

The analysis of the previous section relies heavily on the assumptions of symmetry and of complete information. In this section these assumptions are relaxed. In particular we examine the case where the benefit functions are of the general form $B^i(\cdot,\cdot)$. The index i refers to a firm's "type" and higher values of i will be taken to indicate stronger preferences for the change to technology Y. We take the set of types to be the unit interval and we assume that all types are *a priori* equally probable, i.e., types are distributed uniformly on $[0, 1]$. (These assumptions are not restrictive and considerably simplify the exposition). We also restrict attention to the two period, two-firm case although we will see that the former aspect is not restrictive.[8]

There are thus two periods, 1 and 2, and each firm can switch at time 1 or time 2 or not at all. As in Section II we rule out reswitching. However as we show in footnote 9, the equilibrium which we develop below with this assumption also has the property that no firm which switches in period 2 would want to switch back.

If we let S denote the action "switch" and let D denote "don't switch", a strategy for player j can be described by the pair σ_1^j: $[0,1] \rightarrow \{S, D\}$ and σ_2^j: $[0,1] \times \{S, D\} \rightarrow \{S, D\}$, i.e., the second round move is conditioned on the player's own type and the opponent's first-period move. Here σ_t describes the strategy for period t and maps the set of player types and history of play to date into the possible actions the firm can take. (Strictly speaking σ_2^i should be conditioned also on whether player i switched at time 1. However, a player who did switch at time 1 has no further decisions to make, and hence σ_2^i can be simplified as above without ambiguity).

We make the following assumptions, which are illustrated in Figure 1:

(A1) $B^i(2, k) > B^i(1, k)$, $k = X$ and Y.

Networks are beneficial. (This is assumption (A1) of Section II, rephrased for the current setting.)

(A2) $B^i(2, Y)$ and $B^i(1, Y)$ are continuous and strictly increasing in i.

This assumption captures what is meant by a "type": higher types (indexed by higher values of i) are more eager to switch to Y, both unilaterally and if the other firm also switches.

(A3) $B^1(1, Y) > 0$ and $B^0(2, Y) < B^0(1, X)$.

Unilateral switching is worthwhile for at least one possible type of firm, and (at the other end of the spectrum) there are some types who would rather remain alone with the old technology than join the other firm with the new technology. This assumption ensures that a firm's decision will at least sometimes depend on its predecessor's decision: this is what makes the model interesting.

(A4) $B^i(2, Y) - B^i(1, X)$ is monotone in i.

If a firm of type i' prefers a combined switch to Y to remaining alone with technology X, then so do all firms with $i>i'$.

A helpful analogy is a political "bandwagon" effect. Politicians considering what position to take on an issue are concerned not only with how strongly they feel about it, but perhaps also with how likely it is that their stand will become the majority view. Intuitively we might expect vigorous opponents to oppose the issue regardless of their expectations.

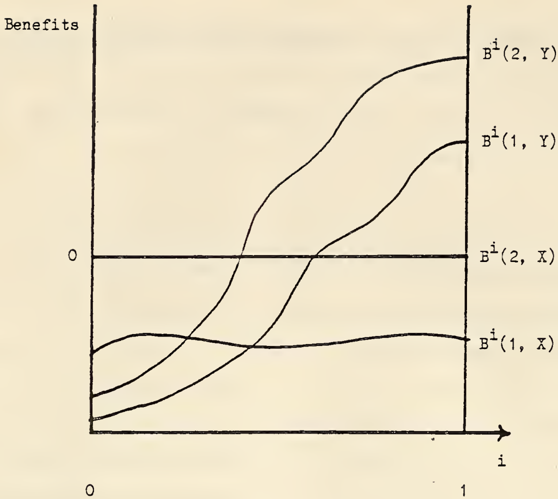


FIGURE 1

Staunch supporters might commit themselves without waiting to see whether it seems that theirs will become the popular view. A more "political" middle group may wait a while to test the political waters, declaring themselves to be "for" the measure if the bandwagon begins to roll, and "against" otherwise. Thus a "bandwagon strategy" for a firm can be defined by a pair $(i^*, \bar{i})$ with $i^* > \bar{i}$ such that:

(i) If $i > i^*$ the firm switches at time 1.

(ii) If $i^* > i > \bar{i}$ the firm does not switch at time 1, and then switches at time 2 if (and only if) the other firm switched at time 1.

(iii) If $i < \bar{i}$, the firm never switches.

A "bandwagon equilibrium" is defined to be a perfect Bayesian Nash equilibrium in which each firm plays a bandwagon strategy. In what follows we will concentrate on symmetric bandwagon equilibria, i.e., those for which $(\bar{i}, i^*)$ is the same for each player. Asymmetric bandwagon equilibria only exist for some specifications of the benefit functions, and will come in mirror-image pairs if they occur. Accordingly, we expect them not to be focal. On the other hand, using only the fairly weak assumptions (A1) - (A4) we show below that a unique symmetric bandwagon equilibrium exists and that there are no equilibria that are not bandwagon equilibria.

Firstly, let $\bar{i}$ be defined by $B^{\bar{i}}(1, X) = B^{\bar{i}}(2, Y)$. Thus any firm with type $i < \bar{i}$ would prefer to remain with the "old" technology than to switch to the "new" technology even if the other firm switched. Clearly, such a firm will never switch. On the other hand, a firm with $i > \bar{i}$ would switch in the second period if the other firm had already switched (and assuming that switching back is known to be ruled out). This essentially describes behavior in the second period[10], and using this we can now analyze the first period.

Now define $f(i) = iB^{i}(2, Y) - \bar{i}[B^{i}(2, Y) - B^{i}(1, Y)]$.

Let $I = \{i\colon f(i) = 0\}$.

<u>Lemma 1</u>: (a) $f(i) < 0 \; \forall \; i < \bar{i}$, (b) $f(i)$ is strictly increasing in $i \; \forall \; i > \bar{i}$,

(c) $f(1) > 0$, (d) I contains exactly one point (which we call i^{*}).

(e) $i^{*} \; \varepsilon(\bar{i}, 1)$

<u>Proof</u>: (a) For $i < \bar{i}$, $\bar{i}B^{i}(2, Y) > i\, B^{i}(2, Y)$.

Therefore also $\bar{i}B^{i}(1, Y) < \bar{i}B^{i}(2, Y) \equiv \bar{i}B^{i}(1, X) < B^{i}(2, X) \equiv 0$.

So $iB^{i}(2, Y) - \bar{i}B^{i}(2, Y) + \bar{i}B^{i}(1, Y) < 0 \; \forall \; i < \bar{i}$.

(b) Immediate since $(i - \bar{i}) > 0$ for $i > \bar{i}$ and since $B^{i}(2, Y)$ and $B^{i}(1, Y)$ are strictly increasing.

(c) $f(1) = B^{1}(2, Y)\,[1 - \bar{i}] + \bar{i}B^{1}(1, Y)$. But $\bar{i} < 1$ (since $B^{1}(2, Y) > 0$) and $B^{1}(2, Y) > B^{1}(1, Y) > 0$.

(d & e) Since $f(i)$ is strictly increasing and continuous on $(\bar{i}, 1]$ with $f(\bar{i}) < 0$ and $f(1) > 0$, there exists exactly one $\bar{i} < i^{*} < 1$ for which $f(i^{*}) = 0$.

<u>Lemma 2</u>: $B^{i^{*}}(1, Y) < 0$ and $B^{i^{*}}(2, Y) > 0$.

<u>Proof</u>: $i^{*}B^{i^{*}}(2, Y) = \bar{i}B^{i^{*}}(2, Y) - \bar{i}B^{i^{*}}(1, Y)$ by the definition of i^{*}.

Therefore $B^{i^{*}}(1, Y) = (\bar{i}-i^{*})B^{i^{*}}(2, Y)/\bar{i}$. Now $\bar{i} > 0$ and $\bar{i} < i^{*}$ imply that $B^{i^{*}}(2, Y)$ and $B^{i^{*}}(1, Y)$ have opposite signs. But then $B^{i}(2, y) > B^{i}(1, Y)$ gives the result.

These Lemmas are illustrated in Figure 2.

We can now prove the following:

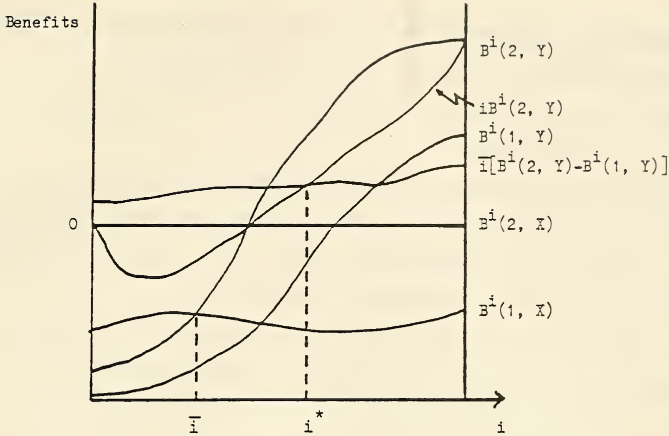


FIGURE 2

Proposition 4: With $\bar{i}$ and i^* as defined above a unique symmetric bandwagon equilibrium exists.

Proof: There are three actions to consider:

a_1: switch at time 1

a_2: switch at time 2 iff opponent switched at time 1

a_3: do not switch at time 2 even if opponent switched at time 1

(There is a fourth possible action, a_4: switch at time 2 if opponent did not switch at time 1; but this is dominated by a_1.)[11]

Let $u^i(a_j)$ be the expected benefit to a firm of type i when it uses action a_j and when its opponent is using the bandwagon strategy $(\bar{i}, i^*)$. The proof proceeds in three steps:

(1) For $i > \bar{i}$ $u^i(a_1) - u^i(a_2)$ has the sign of $i - i^*$.

Proof: $u^i(a_1) = B^i(2, Y)(1-\bar{i}) + B^i(1, Y)\bar{i}$.

$$u^i(a_2) = B^i(s, X)i^* + (1-i^*)\, B^i(2, Y) = (1-i^*)\, B^i(2, Y).$$

Therefore $u^i(a_1) - u^i(a_2) = f(i)$. The result follows from Lemma 1.

(2) $u^i(a_2) - u^i(a_3)$ has the sign of $i-\bar{i}$.

Proof: $u^i(a_2) = B^i(2, Y)(1-i^*)$.

$$u^i(a_3) = B^i(1, X)(1-i^*).$$

The result follows from (A4) and the definition of $\bar{i}$.

(3) If $i \leq \bar{i}$, a_3 is a dominant strategy.

Proof: If $i > \bar{i}$, a_2 is preferred to a_3 [from (2)] and if $i > i^*$, a_1 is preferred to a_2 [from (1)]. Therefore the bandwagon strategy $(\bar{i}, i^*)$ is the unique best-response to the bandwagon strategy $(\bar{i}, i^*)$.

Finally, a symmetric equilibrium has $f(i^*) = 0$ by step (1). But then Lemma 1 implies that there is a unique symmetric bandwagon equilibrium. This proves Proposition 4.

Several features of the equilibrium can be observed directly from Figure 2. As Lemma 2 shows there is a region below i^* where $B^i(2, Y) > 0$. If both firms are of types that fall into this region, the switch will not be made although it would have been made in a world of complete information and although both firms would then be better off. There is symmetric excess inertia! The intuition is clear. Both firms are fence-sitters, happy to jump on the bandwagon if it gets rolling but insufficiently keen to set it rolling themselves.

In addition there is also asymmetric excess inertia. One firm may be of the kind discussed above ($B^i(2, Y) > 0$ and $i<i^*$) but the other firm may have $B^i(2, Y) < 0$. There will always exist some cases where $B^i(2, Y) + B^{i'}(2, Y) > 0$ and $i,i'<i^*$. Here again the switch will not be made even though the sum of the benefits is positive. Finally, it is possible that the switch will be made even though the sum of the benefits is negative. This occurs when one of the firms favors the switch and, although the other opposes it strongly, the latter prefers to switch rather than remain alone with the old technology. Excess "momentum" of this kind will not always exist, but can occur for appropriately specified benefit functions.

Notice too that there are some types in the region $i^*>i>\bar{i}$ for whom $B^i(2, Y) < 0$. These firms will switch if the other firm switches but would have preferred that the new technology had not came along at all. If polled about their intentions *ex ante* they would vehemently claim that they would not switch even if the other switched.[12] This motivates examining the question of communication, to which we turn in the next section.

There are also some types just above i^* for which $B^i(1, Y) < 0$. These types start the bandwagon rolling, but if it turns out that the other firm was of a type below $\bar{i}$ (so that their lead is not followed) they regret their decision <u>ex post</u>. Here again there is a straightforward intuition. Types in this range are sufficiently in favor of technology Y to take the chance of starting the bandwagon even though they know that with positive probability they are up against an "intransigent" with type less than $\bar{i}$ and will end up worse off if this turns out to be so.

There are a number of interesting comparative static results. Consider increasing $B^i(2, Y)$ or decreasing $B^i(1, X)$ until $B^0(2, Y) > B^0(1, X)$ (removing Assumption (A3)), so that every type of firm would follow if the other firm switched. In that case
$\bar{i} = 0$ and so $f(i) = iB^i(2, Y)$. Therefore i^* is defined by $B^{i^*}(2, Y) = 0$. This means that in equilibrium if the switch is socially beneficial for both firms, they will both switch at time 1! Thus in the absence of the intransigents with $i<i^*$, symmetric excess inertia disappears. In addition (trivially) the inertia that arises when only one firm favors the switch also disappears here. Excess momentum can, however, still arise. This bias in favor of switching arises from the assumption that switching back from Y to X cannot occur.

As one would expect, as $B^i(1, Y)$ increases towards $B^i(2, Y)$, i^* decreases until the point defined by $B^{i^*}(2, Y) = 0$. As $B^i(1, Y)$ decreases, i^* increases, and tends to 1 as $B^i(1, Y)$ becomes sufficiently low.

Finally we demonstrate that there are no equilibria that are not bandwagon equilibria:

Proposition 5: any equilibrium strategy is a bandwagon strategy.

Proof: Firstly, we have $\sigma_2(S, i) = \begin{cases} S \text{ if } i \geq \bar{i} \\ D \text{ if } i < \bar{i} \end{cases}$

by perfectness. Further, $\sigma_2(D, i) = D$ for all i (see footnote 11). Consider firm 1's decision. Suppose it assesses probability 1-q that firm 2 will switch at time 1. Then if it waits until time 2 it earns $B^i(2, Y)(1-q) + B^i(2, X)q = B^i(2, Y)(1-q)$. If it switches at time 1 it earns $B^i(2, Y)(1-\bar{i}) + \bar{i}\, B^i(1, Y)$. It pays to switch if $B^i(2, Y)q - \bar{i}[B^i(2, Y) - B^i(1, X)] \geq 0$, which is monotone in i. Therefore if it is optimal for any higher type to switch at time 1, then it is also optimal for type i", i" > i'. So any optimal strategy involves a cutoff at time 1. But then any equilibrium strategy is a bandwagon strategy.

IV. The Model with Incomplete Information and Communication

The analysis of the previous section shows that incomplete information introduces excess inertia in which the new technology is not adopted even when this is favored by both firms. It seems plausible that allowing even a minimal amount of coordination between the firms would eliminate such "symmetric" or "Pareto" inertia. In particular if we allow a single public statement by each firm as to whether it favors the switch before any actions are taken, this problem disappears. Any type i for which $B^i(2, Y) > 0$ would have no incentive to hide this fact and could be expected to announce truthfully. If both firms so announced we would expect technology Y to be adopted. Similarly any type of firm with $i<\bar{i}$ could be relied on to truthfully reveal its type. Only those types of firm for whom $B^i(2, Y) < B^i(2, X)$ and $B^i(1, X) < B^i(2, Y)$ should be expected to misreport.[11] This is the group who would "jump on the bandwagon" once it got going but who would rather the bandwagon had not started at all.

Formally, we model this by adding a period to the beginning of the two-period model of the previous section. At time 0 each firm (simultaneously) announces F or A ("for" or "against") the switch.[13] Time 1 and time 2 are then as before.

A strategy now stipulates for each type, what announcement to make and whether or not to switch at times 1 or 2 (as a function of all available information). We will demonstrate below that the following strategies constitute a perfect Bayesian Nash equilibrium to this game with communication:

(a) Announce F iff $i>i^0$ where i^0 is defined by $B^{i^0}(2, Y) = 0 = B^{i^0}(2, X)$; i.e. iff $B^i(2, Y) > 0$.

(b) If both firms announce F, both switch at time 1.

(c) If both firms announce A, neither switch at time 1 or time 2.

(d) If one firm announces F and the other announces A, employ a bandwagon strategy $\{i', \bar{i}\}$ where $\bar{i}$ is as before and i' is defined by: $B^{i'}(2, Y)i^0 = \bar{i}[B^{i'}(2, Y) - B^{i'}(1, Y)]$.

The only part of the description of equilibrium that requires explanation is part (d). We provide a discussion rather than a formal proof which would largely mimic the proofs of Propositions 4 and 5.

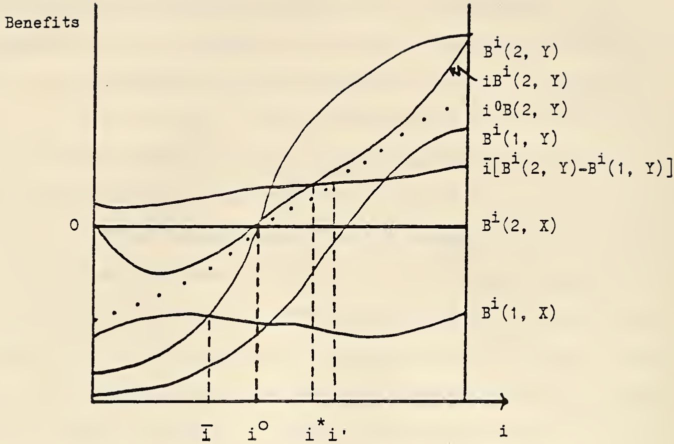
The major change from the no-communication case is in each firm's subjective probability assessment that it will be joined if it initiates a switch. Previously this was merely the probability $(1-\bar{i})$. Now, however, if the other firm has announced "N" this probability is given by $\text{Prob}\{i>\bar{i} \mid i<i^0\}=(i^0-\bar{i})/i^0 = 1-\bar{i}/i^0$. Since $i^0<1$, we have $(i^0-\bar{i})/i^0 < (1-\bar{i})$. This merely says that a firm is more pessimistic that it will be joined in a switch if the other firm has announced "N".

In showing that these strategies form an equilibrium, a typical calculation is the following: should a type i>i' deviate to a strategy of switching at time 2 if the other firm switches at time 1, from its proposed strategy of switching at time 1? Under its current strategy it earns

$$B^i(2, Y)\Pr\{j>\bar{i} \mid j<i^0\} + B^i(1, Y)[1-\Pr\{j>\bar{i} \mid <i^0\}]$$
$$= B^i(2, Y)(1-\bar{i}/i^0) + B^i(1, Y)(\bar{i}/i^0)$$
$$= B^i(2, Y) - \bar{i}/i^0[B^i(2, Y) - B^i(1, Y)].$$

If it deviates to the alternative suggested strategy it earns $B^i(2, X) \equiv 0$ with certainty (since the opponent has announced N). The deviation pays if and only if: $B^i(2, Y)i^0 < \bar{i}\,[B^i(2, Y) - B^i(1, Y)]$.

It is this that motivates the definition of i' given above. This is illustrated in Figure 3.



Benefits
0
$B^i(2, Y)$
$iB^i(2, Y)$
$i^0B(2, Y)$
$B^i(1, Y)$
$\bar{i}[B^i(2, Y)-B^i(1, Y)]$
$B^i(2, X)$
$B^i(1, X)$
$\bar{i}$
i^o
i^*
i'
i

Figure 3

Notice that for all $i>i^0$, $iB^i(2, Y) > i^0B^i(2, Y)$. Therefore $i'>i^*$. This means that a strictly smaller set of types will initiate the switch in the communication case when announcements differ than in the no-communication case. As a result, "excess momentum" and "excess inertia" of the kinds that arise when the preferences of the firms differ, are respectively lower and higher than in the no-communication case. Thus, while communication in the form of a "straw vote" eliminates excess inertia where the preferences of the firms coincide, it increases inertia where the preferences differ.

V. Strategic Technology Adoption by a Dominant Firm

The models developed in Sections II-IV examined the problems of coordinating innovation in an industry in which products not compatible with others are at a substantial disadvantage. The basic premise was that a firm would prefer to be joined by other firms in a move to the new technology. However, while it may be costly for a firm to make a unilateral change to a new technology, this action will also adversely affect the position of the firms that remain with the old technology since their network benefits will have diminished. Where the firms are competitors it is quite possible that this ability to impose a cost on its rivals will induce a firm to make inefficient technology adoption decisions, especially where an increase in concentration results. The following example illustrates this point, which is similar in spirit to the work of Salop and Scheffman (1983).

Consider a duopoly where firm 1 is the "dominant firm" which we model by endowing it with a Stackelberg leadership position.[14] The industry inverse demand function is given by $P = 16 - Q$, where $Q = q_1 + q_2$ and q_i is the output of firm i. As above there are two possible technologies, X and Y, and X is the status quo. The network effect is captured as follows:[15] If both firms use the same technology they have zero marginal costs, but if they differ, marginal costs are 4 per unit. The firms have fixed (but not sunk) costs of $F = 15$ and it costs each firm $S = 2$ to switch from X to Y.

	Firm 1	Firm 2	q_1	q_2	P	Π^1	Π^2
1	X	X	8	4	4	17	1
2	Y	Y	8	4	4	15	-1
3	Y	X	6	3	7	1	-8
4	Y	0	6	0	10	19	0
5	X	Y	6	3	7	3	8

Initially the industry is profitable for both firms (row 1). However, if firm 1 switches to Y, firm 2 will make a loss whether it also switches (row 2) or remains with X (row 3). Therefore, firm 2 would prefer to leave the industry than to follow firm 1. But as row 4 shows, firm 1 prefers the monopoly position and driving firm 2 out of the industry to remaining at the *status quo*The increase in concentration increases firm 1's profits enough to cover both the switching cost S and the increase in variable costs from 0 to 4 that firm suffers. (Row 2 also shows that firm 2 cannot drive firm 1 out since if it switches firm 1 can remain profitable by following the switch to Y.)

Thus the unique perfect equilibrium involves firm 1 switching to Y and firm 2 leaving the industry. Compared to the status quo, this results in an increase in price (from 4 to 7) and a decrease in the sum of consumer and producer surplus (from 90 to 37).

VI. Conclusion and Further Directions.

In this paper, we have analyzed the problem of coordinating innovation in an industry in which products not compatible with others are at a substantial disadvantage. We have shown that there can be inefficient inertia, or inefficient innovation, and that these problems cannot be entirely resolved by communication among firms. We have also discussed the possible use of technology choice to manipulate market structure.

There are several branches of related work. First, there is a large literature (see, e.g., Kamien and Schwartz (1982) and Mansfield (1968)) on dissemination of a new process through an industry. This differs from our work in that there is not the coordination-problem and network benefits aspect we consider. Secondly, Schelling (1978, ch. 4-5) discusses models in which agents of different types can go to any number of "locations"; each agent has preferences on the proportions of different types where he goes. While this (like much of Schelling's work) has aspects of the coordination problem, we do not see a precise analogy. Finally, the model presented in Section V is in the spirit of the models of raising rivals' costs in Salop and Scheffman (1983).

Some important topics we have left untouched, but which would be appropriate for further work, are the following:

(1) In reality, a standard is often a more complex object than we have implictly assumed by supposing that a firm either "adopts" or "does not adopt". In particular, compatibility need not be symmetric: for example, a computer company can try to arrange that software written for its

competitors' machines will run on its machines, but not vice versa. A somewhat similar contest produced the peculiarly shaped holes in old fashioned safety razor blades. This, of course, represents an attempt to get network externalities for oneself while denying them to competitors.

(2) The literature on optimal product diversity (see e.g. Salop (1979)) assumes that the benefits from standardization come from production economies of scale. It would be interesting to analyze the trade-off with variety if the benefit from reduction in variety came from consumer-side network externalities.

(3) All our models above are timeless in the sense that, in the end, payoffs are determined only by <u>who</u> has adopted a standard, not by <u>when</u>. In some cases, there may be benefits to early adoption of what later becomes an industrywide standard: the first-mover advantage. On the other hand, it may be costly to be incompatible with the bulk of the industry for the length of time it takes for them to follow; and, of course, there is a possibility that they may not follow. Thus, even apart from bandwagon effects, timing becomes an interesting issue. (For some related work, see Wilson (1984)). To address these issues of timing Rohlfs (1974) considered an adjustment process in which (in contrast to the present work) consumers choosing whether or not to subscribe to a communications service with network externalities make their decisions on the basis of <u>current</u> payoffs. He exhibits multiple equilibria and critical-mass phenomena, analogies to which could occur here too. Dybvig and Spatt (1983) develop and analyze government incentive schemes to deal with the externalities that arise in a model like that of Rohlfs.

We are working on these and related issues, and we believe there are many other interesting questions in the area waiting to be investigated.

APPENDIX

Proofs of Proposition 2 and 3

We begin by proving three Lemmas to get Proposition 2.

Lemma A. If $n = 2$, each firm prefers to go first.

Proof: Call the firms A and B, and their decisions (X or Y) k_A and k_B. Let (k_A, k_B) be an equilibrium when A goes first. Then, as pointed out above, because of the coordination nature of the game, k_A is A's best response to k_B. Therefore B can achieve his payoff from (k_A, k_B) if he moves first, simply by choosing k_B as before. Of course, B may be able to do better by making another choice when he goes first.

Lemma B. Whatever n may be, any firm would prefer to be #1 than #2.

Proof: This follows from Lemma A, if we collapse the responses of firms 3, 4,...,n into the payoffs for firms A and B who are trading places 1 and 2. All that needs to be checked is that the reduced game continues to satisfy (A1), and that is clear.

Lemma C. For any n, and any $j=1,2,\ldots,(j-1)$ a firm in position $(j+1)$ would like to trade places with the firm in position j.

Proof: Lemma B assures us that this would be true if we could think of the actions of $1,2,\ldots,(j-1)$ as not responding to the change. We then must show that any response by the early players will be favorable to the firm (call it B) which has switched from $(j+1)$ to j.

The reason this is true that the swtich has made the consolidated response function of players j, j+1,...,N (considered together) more in line with B's preferences (Lemma 1). Therefore players 1,...,(j-1), considered as playing a game with the responses of j,j+1,...,n collapsed into the payoff functions, have had their preferences shifted in the direction of B's desires.

Proposition 2 now follows by repeated application of Lemma C. That is, to show that, given the order of the other (n-1) firms, a firm prefers to be earlier in that sequence rather than later, one simply imagines the firm repeatedly moving up one place and bumping its predecessor one place down (as in progress up a squash ladder). This proves Proposition 2.

Proof of Proposition 3.

We actually prove a stronger version of Proposition 3:

(i) Let e_1 and e_2 be perfect equilibria of the game with fixed orders of moves, as in Propositions 1 and 2. Let $S(e_1)$ be the set of firms that switch in equilibrium e_1 and $S(e_2)$ those who switch in e_2. Then there exists another order of moves with its perfect equilibrium e, such that $S(e_1) \cup S(e_2) \subseteq S(e)$.

(ii) There exists an order of moves giving a perfect equilibrium e^* such that $S(e^*)$ is the union of all sets S(e) for equilibria e.

(iii) If moves are in endogenous order then the set $S(e^*)$ of firms will switch to Y.

Proof: Begin with the equilibrium e_1. Preserving the order of moves within $S(e_1)$ and $N-S(e_1)$, move the members of $S(e_1)$ to the front. (So, for instance, if n=5, and $S(e_1) = \{2,4\}$, then we would have a new order of moves

2, 4, 1, 3, 5.) It is clear that, in this new order, <u>at least</u> all the firms in $S(e_1)$ will switch. Now, leaving fixed the order of $S(e_1)$, rearrange the members of $N-S(e_1)$ so that the members of $S(e_2)\setminus S(e_1)$ come immediately after the members of $S(e_1)$, and come in the order they took in e_2. It should now be clear that, with the moves in that order, all the members of $S(e_1)\cup S(e_2)$ will choose Y. This proves the first part of Proposition 3. To clarify the somewhat involved rearrangement, we now give an example to illustrate.

Let $n = 5$, $S(e_1) = \{2, 4\}$ when the order is 12345 (e_1)

$S(e_2) = \{3, 4, 5\}$ when the order is 14532 (e_2)

Then we first change 12345 to 24135 (bringing the elements of $S(e_1)$ to the front). Next, keeping 24 fixed at the front, we rearrange 135 so that 5 and 3 are brought forward, and placed in that order because that is how they appear in e_2. Thus we have 24531. In this order, 2,3,4 and 5 will all switch.

The second claim of Proposition 3 follows by repeated application of the first part.

The final claim, that all firms in $S(e^*)$ will switch if the timing of moves is endogenous, can be shown by induction on n as follows: the first firm to move in e^* can move rapidly and choose Y. (If he were not the first to move, it would be because another firm had committed to Y, since "moves" X really count, as they are reversible.) He can then rely on the (inductively assumed) proposition for the remaining firms to ensure that the maximal set, i.e. $S(e^*)$ less himself, of the others will choose Y. This puts everyone in the same position as in e^* itself, so the outcome is that $S(e^*)$ will switch. This proves Proposition 3.

Footnotes

[1]Other examples of industrial standardization include plugs and sockets (not internationally standardized; and in the U.S. the "polarized" plug is making headway), typewriter keyboards, the ASCI character sets for computers, 35mm. film, light bulbs, records and record-players, etc. Some examples of commodities that might usefully be standardized, but are not, include: video cassette recorders, many auto parts,....

[2]However, the bulk of standardization seems to be done through voluntary industry committees (see Kindleberger (1983)). This encourages us in our interpretation of standardization as due mainly to network externalities as felt by producers. It has also attracted at least some scrutiny by antitrust authorities: see F.T.C. (1983).

[3]To be clear, what we have in mind is that those producers who adhere to the standard do so purely because, given that others do, they wish to. There is neither a standard-enforcing authority nor a system of binding though voluntary contracts to adhere to standards, though both of these potential institutions would be interesting to analyze.

[4]We wish to analyze the bandwagon effect here: it does not seem that any useful purpose would be served by allowing for entry-exit decisions. See Section V, however.

[5]From the timing of political primaries, this might be called the New Hampshire Theorem.

[6]For example, in "matching pennies", players move simultaneously, because moving first would be a fatal disadvantage.

[7]In other words, for each equilibrium e, let S(e) denote the set of firms who switch in e: then S^* is the union of all the sets S(e).

[8]With n firms, suppose that there were $m > n$ periods, and in period i there was both positive probability that some would switch and positive probability that none would. With symmetric strategies, if none switched in period i, then every firm would become uniformly more pessimistic about others' willingness to switch, and therefore (having decided agaist switching at period i) would never switch. If a firm were going to switch after receiving the bad news this would mean it was going to switch anyway, but the strategy of waiting is dominated by switching immediately.

This means that n periods suffice to analyze the n-firm case.

[9]We could assume that it is prohibitively costly to switch back to X in period 2 after switching to Y in period 1. See the brief discussion in Section II. We could alternatively investigate the condition on the B function to ensure that such re-switching would never occur: anticipating the notation about to be developed, a sufficient condition is

$$\frac{i^* - \bar{I}}{i^*} B^{i^*}(2, Y) + \frac{\bar{I}}{i^*} B^{i^*}(1, Y) \geq \frac{i^* - \bar{I}}{i^*} B^{i^*}(1, X) + \frac{\bar{I}}{i^*} B^{i^*}(2, X).$$

Using the definition of i^*, and the fact that $B^{i^*}(2, X) = 0 \geq B^{i^*}(1, X)$, we can see that this condition is always satisfied. We do not fully understand this remarkable conclusion.

[10]The only thing left to specify is what happens in the second period if neither switched in the first. We show below (Proposition 5) that neither firm will switch. See also footnote 11.

[11]If a firm's opponent if of a type below $\bar{I}$, a_1 and a_4 yield the same payoff $B^i(1, Y)$. If the opponent is of a type above $\bar{I}$, a_1 yields $B^i(2, Y)$, whereas one can easily show that a_4 gives a positive probability of $B^i(1, Y)$, and complementary probability of $B^i(1, Y) < B^i(2, Y)$, this concludes the argument.

[12]The purpose of this lie would be to dissuade the other from switching, if the other had $B^i(2, Y) > 0 > B^i(1, Y)$.

[13]A more elaborate -- even a multi-stage -- system of communication before play begins would reduce to this in effect. The reason is that each player either wants to encourage the other to switch, or wants to discourage him, and this preference depends only on the player's own type, not on the other's. Thus we get "bang-bang" communication strategies.

[14]This is done for convenience. Similar effects would arise even in an entirely symmetric oligopoly model, although it would then be less clear who would leave after a change which made the technologies incompatible.

[15]This fits more naturally into the framework of producers exploiting efficiencies of production of inputs by standardization, as with certain auto parts (see Hemenway (1975), especially pages 13-16). However, the essential point that sellers are better-off (other things equal) being compatible, will be the same with consumer-generated benefits.

References

Dybvig, P.H. and C. Spatt (1983) "Adoption Externalities as Public Goods", Journal of Public Economics, Vol. 20, 231-248.

Farrell, J. (1982) "Communication In Games", mimeo, M.I.T.

Federal Trade Commission, (1983) "Standards and Certification: Final Staff Report".

Hemenway, D. (1975) Industrywide Voluntary Product Standards, Cambridge, MA, Ballinger.

Kamien, M.I., and Schwartz, N.L. (1982) Market Structure and Innovation, Cambridge: Cambridge University Press.

Katz, N. and C. Shapiro (1983) "Network Externalities, Competition, and Compatibility", Woodrow Wilson School Discussion Paper #54, Princeton.

Kindleberger, C.P. (1983) "Standards as Public, Collective and Private Goods", Kyklos, Vol. 36, 377-397.

Mansfield, E. (1968) The Economics of Technological Change, New York: Norton.

Rohlfs, J. (1974) "A Theory of Interdependent Demand for a Communications Service", Bell Journal of Economics, Vol. 5, 16-37.

Salop, S.C. (1979), "Monopolistic Competition with Outside Goods", Bell Journal of Economics, Vol. 10, 141-56.

Salop, S. C. and D.T. Scheffman (1983) "Raising Rivals' Costs", American Economic Review, Vol. 73, 267-271.

Schelling, T. (1978) Micromotives and Macrobehavior, New York: Norton.

Wilson, C. (1984), "Games of Timing with Incomplete Information", mimeo, N.Y.U.