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Standardization, compatibility, and innovation

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There are often benefits to consumers and to firms from standardization of a product. We examine whether these standardization benefits can "trap" an industry in an obsolete or inferior standard when there is a better alternative available. With complete information and identical preferences among firms the answer is no; but when information is incomplete this "excess inertia" can occur. We also discuss the extent to which the problem can be overcome by communication.

1. Introduction

■ Many goods are "compatible" or "standardized" in the sense that different manufacturers provide more interchangeability 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 personal computer software. There may be a market-mediated effect, as when a complementary good (spare

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[1] Other examples of industrial standardization include plugs and sockets (not internationally standardized; and in the United States the "polarized" plug is making headway), typewriter keyboards, the ASCI character sets for computers, 35 mm. 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, etc. A source of some interesting history is Hemenway (1975).

[2] The bulk of standardization, however, seems to be done through voluntary industry committees (Kindleberger, 1983). This encourages us in our interpretation of standardization as owing mainly to network externalities as felt by producers. It has also attracted at least some scrutiny by antitrust authorities (U.S. Federal Trade Commission, 1983).

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' incentive to make their products compatible. In addition, some kinds of standardization will allow producers to get inputs more cheaply by exploiting 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'. This incentive does not, however, necessarily correspond exactly to social benefits.

Katz and Shapiro (1983) develop an oligopoly 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, since that would increase 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 article. Intuitively, it is plausible that the industry, once firmly bound together by the benefits of compatibility or standardization, will be inclined to move extremely reluctantly to a new and 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 when retraining costs are considered: the reason for its persistence is (supposedly) the overwhelming benefit from compatibility.[3] In this article we study the possibility that this "excess inertia" impedes the collective switch from a common standard or technology to a possibly superior new standard or technology.[4]

In Section 2 we study 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 would benefit from the change, then all *will* change! In other words, there is no excess inertia impeding the change. Both unanimity and complete information are necessary for this result, however. We discuss the complete-information model with different preferences, but the focus of the article is on the incomplete-information model.

In Section 3 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 strongly favor the change switch early, while those that only moderately favor wait

[3] David (1984) cites a U.S. Navy study which found that the payback period for retraining typists with the Dvorak keyboard was only ten days. This implies present values of time savings very much in excess of plausible costs for converting the physical stock of typewriters, especially since golfball typewriters would only require a new golfball and some stickers for the keys, while word-processing computers can also be cheaply converted.

[4] Arthur (1983) has modelled the evolution of a standard in an industry with network externalities and shows how, in a simple model, the realization of early random events can affect the standard chosen. Our work is concerned with the behavior of an industry that has already adopted a standard and is considering switching to a new one.

to see whether others will switch and then get on the bandwagon if it in fact gets rolling. If that happens, some who oppose the change will ultimately adopt it. Among those who first get on the bandwagon are some types of firms that will regret switching if in fact they are not followed. They sufficiently favor the change, however, to be willing to take that risk; the compensating benefit is the hope that they will precipitate the bandwagon effect.

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

Symmetric inertia is purely a problem of coordination. Hence, one might expect that, as in Farrell (1982), nonbinding communication of preferences and intentions may eliminate the inertia. We show in Section 4, however, that while this indeed eliminates the symmetric excess inertia, it exacerbates the problem of asymmetric inertia.

In Section 5 we present our conclusion and suggest avenues for future research.

2. A model with sequential decisions and complete information

■ One of the clearest features of noncooperative[5] standard setting is its bandwagon quality. When compatibility is an important consideration for a firm setting its product specifications, early movers can influence later movers' decisions: if firm 1 switches to a new standard, then firm 2 will find switching more attractive 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.

While the sequential timing may seem artificial, we can show that every equilibrium we derive is also an equilibrium in the simultaneous-move game. Moreover, the equilibrium if timing is endogenous (see below) is one of those we now consider.

Let $N = \{1, 2, \ldots, n\}$ denote the set of firms in the industry. For any $j \in N$ 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 its benefit if all firms stick with X. In other words, we normalize so that each firm gets zero benefit in the *status quo.* 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 favor 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 $N \setminus S$ switch to Y. Thus, in particular, $B_j(N, X) = 0$ by normalization.

The basic *assumption of positive network externalities* can now be phrased by Assumption 1.

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

Assumption 1. 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 others make the same choice. This introduces the coordination considerations that are the focus of this article.

□ **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 shall sometimes assume that the function $B_j(\cdot, \cdot)$ is the same for all j, so we can simply write $B(m, X)$ or $B(m, Y)$.

□ **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. (Since one firm has a decision each period, the number of periods is equal to the number of firms.) In period j, firm j decides whether to switch to Y. If S denotes the set of firms that do switch, then the payoffs are

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

$$B_j(N \setminus S, X) \quad \text{for} \quad j \notin S.$$

Proposition 1. Suppose that, for each j,

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

Then the unique perfect equilibrium involves all firms' switching.

Proof. The condition (1) ensures that, for each j, if $1, \ldots, j-1$ 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 then switch). Since j knows this is true for $j+1, \ldots, n$, he knows they will switch if he does; and so he will switch.

Notice that Proposition 1 does not use Assumption 1. Using that assumption yields the following result.

Corollary. If

$$B_j(N, Y) > B_j(N, X) \text{ for all } j, \tag{2}$$

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 firm prefers an overall industry switch but it fails to happen.*

Condition (1) is weaker than unanimity (2), however. So Proposition 1 tells us that players j, 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 find excess inertia or its opposite if we make judgments based on adding benefits.

Being late in the game is a strategic disadvantage because of our assumption that each agent has only one chance to choose his standard; thus, early movers are able to commit. In a game of complete information, there is no countervailing value to waiting to see how things evolve. 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.[6]

Proposition 2 is proved in the Appendix. It uses only the presence of network

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

externalities—Assumption 1. 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 von Stackelberg follower has moved, the leader would like to change his move, if he could.[7] 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 3.

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 moves first, then he will switch and B will follow. If B moves 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 moving first.

□ **Endogenous timing and a bias for switching.** Hitherto, we have had no essential strategic 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 reversion 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 make their decisions in a prespecified 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 one most inclined to Y that will occur.

To make this precise, we introduce the following notation. Let e be any perfect equilibrium with a prespecified order of moves. Write $S(e)$ for the set of firms that switch to Y in that equilibrium. Now define S^* to be the union of all the sets $S(e)$, where e ranges over all possible orders of moves.

Proposition 3. When timing is endogenous as above, then all firms in S^* switch to Y.

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.

[7] For example, in "matching pennies," moving first would be a disadvantage.

3. A model with incomplete information

■ The analysis of the previous section relies heavily on the assumption of complete information. This assumption seems somewhat unrealistic, however, especially in view of its strong implications. In reality, a firm will generally be uncertain whether it would be followed if it switched. In this section we study a somewhat different model in which we represent that uncertainty as incomplete information about the other firm's preferences. We also allow for endogenous timing of moves, as above, but find that in conjunction with the incomplete information this yields a richer set of possibilities than Proposition 3 would suggest.

Since we are explicit about incomplete information and differences among firms, we can write the benefit function as $B^i(\cdot, \cdot)$, where i denotes a firm's type, and where there is now no need to subscript $B(\cdot, \cdot)$, since any differences are captured in different values of i. 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 shall see that having more than two periods would not change the results.[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 2 we rule out reswitching. As we show in footnote 9, however, the equilibrium which we develop below with this assumption also has the property that no firm that switches in period 1 would want to revert.

If we let S denote the action "switch" and let D denote "do not switch," a strategy for player j can be described by the pair

$$\sigma_1^j\colon [0, 1] \to \{S, D\} \qquad \text{and} \qquad \sigma_2^j\colon [0, 1] \times \{S, D\} \to \{S, D\},$$

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. A player who did switch at time 1 has no further decisions to make, however, and hence σ_2^i can be simplified as above without ambiguity.)

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

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

Networks are beneficial. (This is Assumption 1 of Section 2, rephrased for the current setting.)

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

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[8] With n firms, suppose that there were $m > n$ periods, and in period i there were both positive probability that some would switch and positive probability that none would switch. 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 against 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.

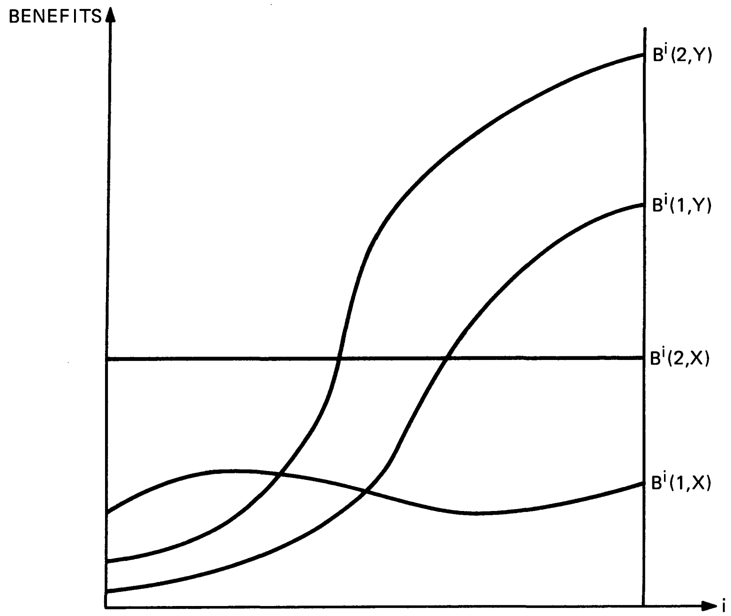
[9] We could assume that it is prohibitively costly to switch back to X in period 2 after switching to Y in period 1. See the brief discussion in Section 2. We could alternatively investigate the condition on the B function to ensure that such reswitching would never occur: anticipating the notation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

FIGURE 1

EXAMPLES OF BENEFIT FUNCTIONS THAT SATISFY THE ASSUMPTIONS OF THE MODEL



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.

Assumption 3. $B^1(1, Y) > 0$ 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 also implies that for intermediate values of i, a firm's decision will at least sometimes depend on its predecessor's decision: this is what makes the model interesting.

Assumption 4. $B^i(2, Y) - B^i(1, X)$ 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 $i > i'$. In other words, if i' would follow a lead, then so would $i > i'$.

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. 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 awhile 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 $i \geqslant i^*$, the firm switches at time 1; (ii) if $i^* > i \geqslant \bar{i}$, 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; and (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 shall 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 1–4, we show below that a unique symmetric bandwagon equilibrium exists and that there are no equilibria that are not bandwagon equilibria.

First, 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 remaining with the "old" technology to switching 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 precluded). This essentially describes behavior in the second period.[10] Using this, we can now analyze the first period.

Define $f(i) = iB^i(2, Y) - \bar{i}[B^i(2, Y) - B^i(1, Y)]$. Let $I = \{i: f(i) = 0\}$.

Lemma 1. (a) $f(i) < 0 \ \forall\ i \leqslant \bar{i}$; (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^*); and (e) $i^* \in (\bar{i}, 1)$.

Proof. (a) For $i \leqslant \bar{i}$, $\bar{i}B^i(2, Y) \geqslant iB^i(2, Y)$. Also $\bar{i}B^i(1, Y) < \bar{i}B^{\bar{i}}(1, Y) < \bar{i}B^{\bar{i}}(2, Y) \equiv \bar{i}B^{\bar{i}}(1, X) < B^{\bar{i}}(2, X) \equiv 0$. So $(iB^i(2, Y) - \bar{i}B^i(2, Y)) + \bar{i}B^i(1, Y) < 0 \ \forall\ i \leqslant \bar{i}$. (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 $f(i^*) = 0$.

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

Proof. $i^*B^{i^*}(2, Y) = \bar{i}B^{i^*}(2, Y) - \bar{i}B^{i^*}(1, Y)$ 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.

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 if and only if 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:

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

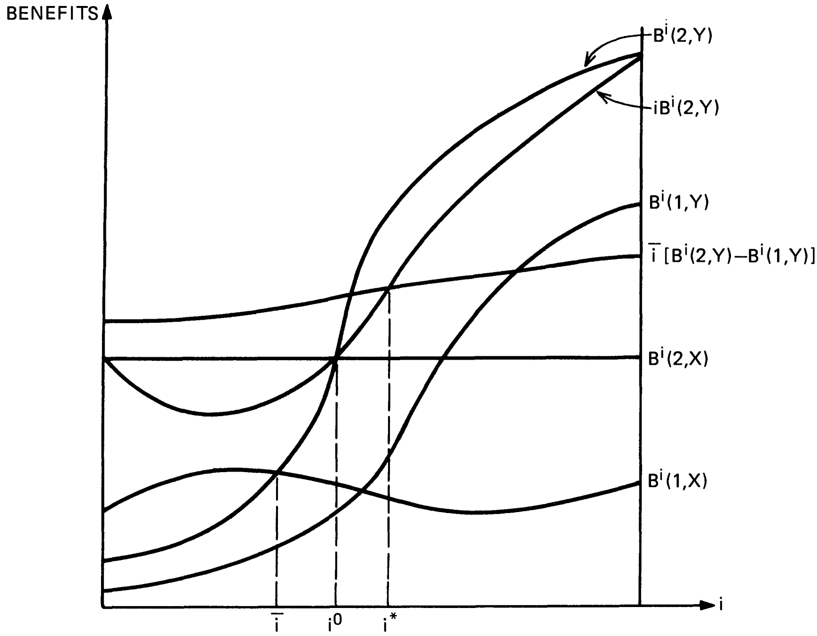
$$u^i(a_1) = B^i(2, Y)(1 - \bar{i}) + B^i(1, Y)\bar{i};$$

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

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

[11] If a firm's opponent is 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.

FIGURE 2
AN ILLUSTRATION OF THE DERIVATION OF THE CRITICAL LEVELS $\bar{i}$, i^0, AND i^*



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

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

$$u^i(a_2) = B^i(2, Y)(1 - i^*);$$

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

The result follows from Assumption 4 and the definition of $\bar{i}$.

(iii) If $i \leq \bar{i}$, a_3 is a dominant strategy. If $i > \bar{i}$, a_2 is preferred to a_3 (from (ii)) and if $i > i^*$, a_1 is preferred to a_2 (from (i)). 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 (i). 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 nonetheless $B^i(2, Y) > 0$. 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 fencesitters, 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 switching to remaining 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 which $B^i(2, Y) < 0$. These firms will switch if the other firm switches, but would have preferred that the new technology had not come 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 *ex post.* Here, again, there is a straightforward intuition. Types in this range sufficiently favor technology Y that they risk starting the bandwagon even though they know with positive probability that 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 3), 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 beneficial for both firms, they will both switch at time 1! Thus, in the absence of the intransigents with $i < \bar{i}$, 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, just as in Proposition 3.

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. First, we have

$$\sigma_2(S, i) = \begin{cases} S & \text{if} \quad i \geq \bar{i} \\ D & \text{if} \quad i < \bar{i} \end{cases}$$

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 type i' to switch at time 1, then it is also optimal for any higher type i'', $i'' > i'$. So any optimal strategy involves a cutoff at time 1. But then any equilibrium strategy is a bandwagon strategy.

4. 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 adoption is favored

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[12] The purpose of this lie would be to dissuade the other from switching, if the other had

$$B^i(2, Y) > 0 > B^i(1, Y).$$

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 firm 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 reveal its type truthfully. 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. This is the group that would "jump on the bandwagon" once it got rolling but that would rather the bandwagon had not started rolling 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 of firm what announcement to make and whether to switch at times 1 or 2 (as a function of all available information). We shall demonstrate below that the following strategies constitute a perfect Bayesian Nash equilibrium to this game with communication:

(1) Announce F if and only if $i \geqslant i^0$, where i^0 is defined by $B^{i^0}(2, Y) = 0 = B^{i^0}(2, X)$; i.e., if and only if $B^i(2, Y) \geqslant 0$.
(2) If both firms announce F, both switch at time 1.
(3) If both firms announce A, neither switches at time 1 nor time 2.
(4) 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 (4). We provide a discussion rather than a formal proof that 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 "A," this probability is given by Prob $\{i \geqslant \bar{i} | i < i^0\} = (i^0 - \bar{i})/i^0 = 1 - \bar{i}/i^0$. 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 "A."

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

$$\begin{aligned} &B^i(2, Y)\,\Pr\{j > \bar{i} | j < i^0\} + B^i(1, Y)[1 - \Pr\{j > \bar{i} | j < i^0\}] \\ &\quad = B^i(2, Y)(1 - \bar{i}/i^0) + B^i(1, Y)(\bar{i}/i^0) \\ &\quad = B^i(2, Y) - \bar{i}/i^0[B^i(2, Y) - B^i(1, Y)]. \end{aligned}$$

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.

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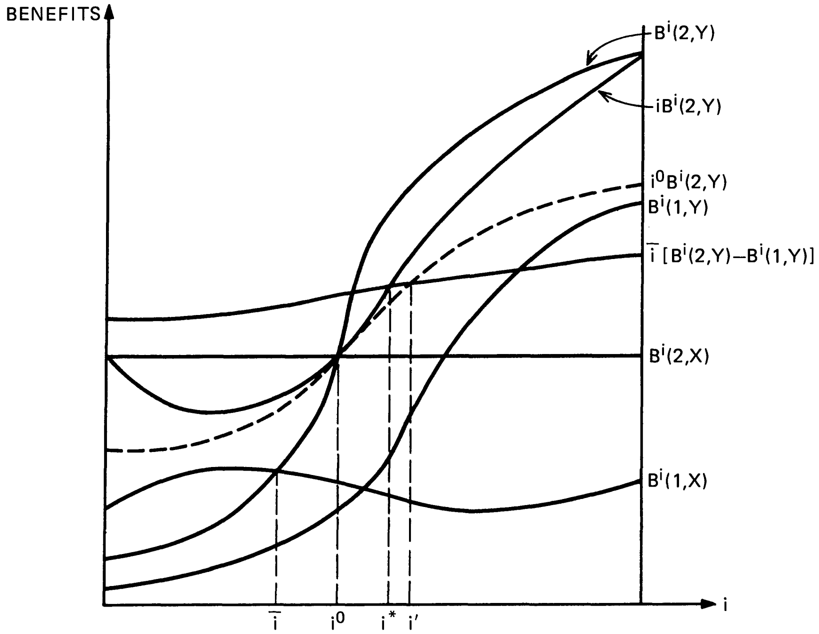
[13] A more elaborate—even a multistage—system of communication before play begins would reduce to this in effect. The reason is that each player either wants to encourage the other to switch, or wants to discourage him, and this preference depends only on the player's own type, not on the other's. Thus we get "bang-bang" communication strategies: one either chooses the most encouraging or the most discouraging communication strategy. Thus, there is no need to consider more than two communication strategies.

FIGURE 3

THE EFFECT OF COMMUNICATION ON THE BANDWAGON EQUILIBRIUM



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.

5. Conclusion and further directions

■ In this article we have analyzed the problem of coordinating innovation or a change of standard 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.

Some important topics which 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 implicitly 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 the 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 (Salop, 1979) assumes that the benefits from standardization come from production economies of scale. It would be interesting to analyze the tradeoff 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 *who* has adopted a standard, not by *when* the standard was adopted. 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 majority of firms in 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 to subscribe to a communications service with network externalities make their decisions on the basis of *current* payoffs. He exhibits multiple equilibria and critical-mass phenomena, analogies to which could also be drawn here. Dybvig and Spatt (1983) develop and analyze government incentive schemes to deal with the externalities that arise in a model like that of Rohlfs.

(4) It is widely believed that "large" firms have a great deal of strategic power in the kind of *de facto* standard-setting we analyze here. This can be examined in the context of our model: a large firm's customers experience relatively little change in their payoff when other firms decide whether to be compatible with the large firm. By contrast, the large firm's decision substantially affects the payoffs to buyers of other firms' products. It is an open question whether this concentration of power leads to distortions in the industry's choice of technology.

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

Appendix

■ The proofs of Propositions 2 and 3 follow.

Proof of Proposition 2. We begin by proving three lemmas to get Proposition 2.

Lemma A. If $n = 2$, each firm (nonstrictly) 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 in the discussion following the statement of Proposition 2, k_A is also 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 (nonstrictly) rather be #1 than #2.

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

Lemma C. For any n, and any $j = 1, 2, \ldots, (j - 1)$ a firm in position $(j + 1)$ would (nonstrictly) 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 is that the switch has made the consolidated response function of players $j, j + 1, \ldots, n$ (considered together) more in line with B's preferences (Lemma 1). Therefore, players $1, \ldots, (j - 1)$, considered as playing a game with the responses of $j, j + 1, \ldots, n$ 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's 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) Consider the game with two fixed orderings of moves. Let e_1 and e_2 be perfect equilibria of the games corresponding to those orderings. Let $S(e_1)$ be the set of firms that switch in equilibrium e_1 and let $S(e_2)$ be those that 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 $N \setminus S(e_1)$, 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, *at least* all the firms in $S(e_1)$ will switch. Now, leaving fixed the order of $S(e_1)$, rearrange the members of $N \setminus S(e_1)$ 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 $S(e_1) \setminus S(e_2)$ 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 1,2,3,4,5 (e_1) and $S(e_2) = \{3,4,5\}$ when the order is 1,4,5,3,2 (e_2). Then we first change 1,2,3,4,5 to 2,4,1,3,5 (bringing the elements of $S(e_1)$ to the front). Next, keeping 2,4 fixed at the front, we rearrange 1,3,5 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 2,4,5,3,1. 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 it were not the first to move, it would be because another firm had committed to Y, since "moves" X do not 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.

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