PRODUCT COMPATIBILITY CHOICE IN A MARKET WITH TECHNOLOGICAL PROGRESS*

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I. Introduction

The benefit that a consumer derives from the use of a good often is an increasing function of the number of other consumers purchasing compatible items. This effect has long been recognized in the context of communications networks such as the telephone and Telex. In these cases, there is a direct externality; the more subscribers there are on a given communications network, the greater are the services provided by that network. Because they were first recognized in these industries, we call these positive external consumption benefits network externalities.

Network externalities are significant in many important industries where there are no physical networks. In fact, most examples of network effects entail indirect externalities associated with the provision of a durable good (hardware) and a complementary good or service (software). In these cases the externality arises when the amount and variety of software available increase with the number of hardware units sold. For instance, computers and programs must be used together to produce computing services, and the greater the sales of hardware, the more surplus the consumer is likely to enjoy in the software market due to increased entry. With video cassette players, the playback machine and a cassette jointly produce video services. Any technology that requires specific training also is subject to network externalities; the training is more valuable if the associated technology is more widely adopted. The arrangement of typewriter keyboards is an often noted example. Similarly, durable goods, such as automobiles, that require specialized servicing often are subject to network externalities.

When network externalities are significant, so too are the benefits to having all consumers purchase units of the durable that can utilize identical units of the complementary good. If two units of hardware can utilize identical units of software, they are said to be compatible. All television sets, for example, are compatible in that they can receive and process the same broadcasts. Understanding the extent to which products will be compatible with one another is central to the analysis of markets in which network externalities arise.

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1With communications networks the question of compatibility has a somewhat different structure. The question is one of whether consumers using one firm's facilities can contact consumers who subscribe to the services of other firms.
There are two ways in which such industrywide compatibility or standardization may be achieved. For some products (e.g., video cassette recorders), the competing technologies may be inherently incompatible. In such cases, the only way to enjoy the full benefits of network externalities is to achieve de facto standardization by having all consumers purchase the same technology. The adoption of the QWERTY keyboard arrangement in the typewriter industry followed this pattern of standardization.\(^2\) Arthur (1985) and Farrell and Saloner (1985 and 1986) study consumer choice among incompatible technologies in a market where the firms do not behave strategically. In Katz and Shapiro (1986), we examine the dynamics of competition between incompatible technologies in a market where firms do engage in strategic pricing.

The second way of exploiting network benefits to their fullest is to design products utilizing different technologies to work with one another. This type of technical compatibility might be thought of as creating a “standardized interface.” By this we mean that each firm continues to produce according to its own technology, but the products of the two firms use the same software or may communicate directly with one another. Typically, achieving technical compatibility will be costly. These costs may include the costs of redesigning the products to work with the same complementary products, or the costs that one firm incurs in producing an adapter that allows its hardware to utilize software designed for the product of another firm. In many markets, this may be done at reasonable cost. For example, the use of standardized interfaces allows a variety of components in a personal computer system to operate together; several different brands of personal computer (the hardware) may utilize a given brand of printer (here, the “software”).

In this paper, we use a modified version of our (1986) model to study the private and social incentives to achieve technical compatibility in the context of dynamic rivalry and industry evolution. The competitive environment is dynamic for two reasons. First, over time each product or network establishes an installed base of physical capital, in the form of previously sold equipment, and human capital, in the form of users who are trained to operate that network’s products. The installed bases at any point in time influence competition at that time, due to the positive network externalities that such bases confer on current adopters. The second source of change in the environment comes from technological progress, which we take as exogenous. The relative costs of competing technologies may shift over time. In the presence of network externalities, it is important for current adopters to form expectations about the future costs of the rival technologies, since these cost will influence the future sizes of the networks among which current consumers must choose. Both the case of known

\(^2\) David (1985) provides an interesting history of the adoption of the QWERTY keyboard as the standard arrangement.
We find that the dynamics of competition have a powerful effect on private compatibility decisions. In an earlier paper, Katz and Shapiro (1985), we showed that in a static environment (i.e., a single-period model) the industry's collective incentives to achieve full compatibility always are less than the social incentives. In our dynamic framework, however, we find that private firms often have excessive collective compatibility incentives. The reason is the following one. When firms produce incompatible products, consumer valuation of a unit of the good depends on the network size of the specific manufacturer of the unit. Thus, in the early stages of industry evolution, there may be extremely intense competition among producers as each seeks to get ahead of its rivals by building up an installed base. With compatible products, however, all brands are part of a single network. Hence, there is no mechanism by which a firm may establish a lead in terms of installed base. Thus, compatibility may serve to diminish competition in a new or rapidly growing industry. The resulting increase in profits is a private, but not social, benefit which gives rise to excessive compatibility incentives.

The paper is organized as follows. In Section II, we formulate a model of dynamic network competition. We describe market equilibria in this model for the case of nonstochastic technological progress, and examine the effect of compatibility on consumers, firms, and aggregate welfare. Section III treats the case of uncertain technological advance. A conclusion follows.

II. Network competition with certain technological progress

We examine the sub-game perfect equilibrium of a three stage game in which there are two competing technologies. We assume that each technology is patented and hence proprietary. At time zero, the firms choose whether to design their products to be compatible. At date \( t = 1 \) each firm selects a price for its product or technology. In response to these prices, each of the \( N_1 \) consumers in the market at \( t = 1 \) chooses which technology to adopt. Again at time \( t = 2 \), each firm sets a price and each of the \( N_2 \) consumers in the market at that time responds. \( N_1 \) and \( N_2 \) are given exogenously. Figure 1 presents a schematic diagram of our three stage game.

The technologies may have different production costs over the two periods. Denote by \( c_t \), the per-unit production cost for technology \( A \) during period \( t \); let \( d_t \), denote firm \( B \)'s unit costs at time \( t \). As we shall see, the crucial variable is the difference between the two technology's costs, which we denote by \( \alpha_t = d_t - c_t \). \( \alpha_t \) measures firm \( A \)'s cost advantage during period \( t \).

Apart from the firms' costs, the problem is symmetric across the two firms. Therefore we can, without loss of generality, adopt the labeling...
Fig. 1. Compatibility choice in a three-stage game

convention that technology B is cheaper during the second period: \( \alpha_2 \leq 0 \). If \( \alpha_1 \) also is negative, then technology B is superior in both periods. The more interesting case will turn out to be the one in which \( \alpha_1 > 0 \). In that case, technology A holds the initial cost advantage, but is overtaken technologically by B in the second period. When \( \alpha_1 > 0 \) and \( \alpha_2 < 0 \), it is useful to think of technology B as the new or emerging technology.

A consumer shopping in period t has a completely inelastic demand for one unit of the good. The gross benefit that a consumer derives from consumption of one unit of the good, \( v(z) \), depends on how many other consumers, \( z \), ultimately purchase compatible units. In other words, the extent of consumption externalities depends only on the final network sizes. Consumers in our model are homogeneous in that all of them have the same surplus function \( v(z) - p \), where \( p \) is the price paid. The prices of technologies A and B in period t are denoted by \( p_t \) and \( q_t \), respectively.

If the products are compatible, each consumer enjoys gross benefits of \( v(N_1 + N_2) \) from either technology, since (under our assumption of inelastic demand) all other consumers ultimately purchase compatible units. When the technologies are incompatible, gross consumption benefits depend upon the number of consumers purchasing the same technology. Let \( x_t \) and \( y_t \) denote the quantities of technologies A and B, respectively, that are sold in period t. A consumer who purchases technology A in period t derives net

As we discuss more fully in Katz and Shapiro (1986), it is straightforward to allow first-period consumers to derive intermediate benefits from the good that depend solely on the first-period network size. Such benefits would only strengthen the incentives for first-period consumers to form a bandwagon.
benefits of \(v(x_1 + x_2) - p_t\). The corresponding value for a consumer who purchases technology \(B\) in period \(t\) is \(v(y_1 + y_2) - q_t\).

A. Equilibrium with compatible products

If the products of the two firms are compatible, consumers in each period purchase units from the firm offering the lower price. This choice generates net benefits of \(v(N_1 + N_2) - \min(p_t, q_t)\) for a consumer in period \(t\). The allocation of first-period sales across firms has no effect on the second-period outcome. In the second period, the firms play a standard Nash-Bertrand pricing game. The equilibrium entails the firm with the lower costs winning all of the second-period sales at a price “just under” the costs of its rival. With our labeling convention that \(\alpha_2 \leq 0\), firm \(B\) wins all of the second-period sales at a price of \(c_2\) and earns second-period profits of \(\pi^B_2 = -N_2\alpha_2\).

The first-period pricing game has the same structure as the second-period one. When \(\alpha_1 > 0\), firm \(A\) captures first-period sales at a price of \(c_1\), earning profits of \(\pi^A_1 = N_1\alpha_1\). For \(\alpha_1 \leq 0\), firm \(B\) wins the first-period sales and earns \(\pi^B_1 = -N_1\alpha_1\) from those sales.

Total industry profits over the two periods are equal to \(N_1|\alpha_1| + N_2|\alpha_2|\). Consumers in period \(t\) enjoy net benefits of \(N_t(v(N_1 + N_2) - \max[c_t, d_t])\). Aggregate welfare, which we take to be the sum of consumer surplus and profits, is simply the excess of gross consumption benefits over production costs. It is given by \(W = (N_1 + N_2)v(N_1 + N_2) - N_1 \min[c_1, d_1] - N_2d_2\).

B. Equilibrium with incompatible products

When the technologies are incompatible, each consumer cares about the adoption decisions of all other consumers. Not surprisingly, bandwagons arise. In fact, in response to any pair of prices \((p_t, q_t)\) in period \(t\), there is no equilibrium in which consumers in that period choose different technologies from one another. To see this fact, consider period two. Given homogeneous tastes, a second-period equilibrium among consumers could involve positive sales of both technologies only if all consumers were indifferent between the two networks. But then a single consumer who was adopting product \(A\) could increase her payoff by shifting to network \(B\). Such a shift would, given the positive consumption externalities, raise the payoff from adopting \(B\) above its previous level, which in turn equalled the consumer’s previous payoff. Therefore, only corner equilibria are possible in the second period. The argument for bandwagon equilibria is even stronger in the initial period. At that time, an individual’s switch from \(A\) to \(B\) might also cause more second-period consumers to adopt \(B\), and cannot cause more of them to choose \(A\). Of course, our strong within-period bandwagon result relies on consumer homogeneity.

\(^4\)If consumers ignored their influence on network size (i.e., if there were a continuum of consumers), then an unstable interior equilibrium might exist.
There may exist more than one perfect equilibrium involving within-period bandwagons.\(^5\) For example, if everyone else chooses technology A at time \(t\), it may well be optimal for any given period-\(t\) consumer also to choose A in order to stay with the crowd. But the same may hold true for technology B. It is our view that the Pareto-preferred equilibrium serves as a focal point when there are multiple equilibria. In particular, we assume that consumers in the market at a given date all select the technology yielding them each the greater surplus when two corner equilibria (for consumer choices at a given date) exist. Note this “coordination” does not require any side payments, since the consumers purchasing at a given date have coincident interests.

Solving the game backwards, we begin with second-period competition. Using the argument above, the only possible histories all entail a single firm having “won,” i.e., having made all of the sales, during the first period. As we shall see, a key feature of a given market is whether the second-period consumers will match the first-period consumers’ technology choice.

The firms play Nash in second-period prices, and thus either firm is willing to go down as far as its marginal cost in order to undercut the other firm. With our Pareto-selection criterion, the technology that can offer second-period consumers the greater level of surplus (were it to price as low as its marginal cost) captures all second-period sales. The winning technology is priced so that it marginally beats the losing one.

Competition in the second period hinges on the two differences between the firms that exist at that time. The first difference is the cost advantage that firm B enjoys, \(-\alpha_2\). The second difference is the installed base advantage that accrues to whichever firm won the sales during the initial period. The firm with the installed base can offer gross benefits of \(v(N_1 + N_2)\) if second-period consumers adopt it. In contrast, the firm with no base can only offer benefits of \(v(N_2)\); effectively, its product is inferior. Formally, the installed base advantage is given by

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\frac{v(N_1 + N_2)}{2} - v(N_2),
\]

the additional benefits that a technology offers due to its already having \(N_1\) users.

Technology B’s second-period cost advantage may be so large that it will be chosen even if technology A is priced at cost in the second period and all first-period consumers purchased A. This will occur if \(v(N_2) - d_2\), the maximum surplus that B can offer without an installed base, exceeds \(v(N_1 + N_2) - c_2\), A’s best surplus offer when it does have a base of users. \(v(N_2) - d_2 > v(N_1 + N_2) - c_2\) is equivalent to \(-\alpha_2 > \beta_2\), i.e., B’s cost advantage exceeds A’s installed base advantage.

Consider first-period competition when \(-\alpha_2 > \beta_2\), recalling that in a perfect equilibrium first-period consumers rationally anticipate second-period pricing and adoption decisions as a function of their own (collective) choice. If first-period consumers opt for technology A, then in the second

\(^5\) We explore the structure of multiple equilibria in our (1985) paper.
period the maximal price that $B$ can charge satisfies 

$$v(N_1 + N_2) - c_2 = v(N_1) - q_2,$$

or $q_2 = c_2 - \beta_2$. Firm $B$ earns total profits of $N_2(-\alpha_2 - \beta_2)$. Alternatively, firm $B$ can undercut firm $A$ in the first period. First-period consumers recognize that second-period consumers will purchase technology $B$. Thus, first-period consumers compare $v(N_1) - p_1$ and $v(N_1 + N_2) - q_1$. Firm $B$ enjoys an anticipated base advantage of $\beta_1 = v(N_1 + N_2) - v(N_1)$. Using the fact that firm $A$ is willing to price as low as $c_1$ to win first-period sales, firm $B$ must set its price at $q_1 = c_1 + \beta_1$ in order to win first-period sales. In this event, firm $B$ earns profits of $N_1(-\alpha_1 + \beta_1)$ in the first period.

Given that technology $B$ prevails during the first period, firm $B$ can set a higher second-period price than it could had it lost in the first period. Its maximal second-period price is $q_2 = c_2 + \beta_2$, generating second-period profits of $N_2(-\alpha_2 + \beta_2)$. Comparing total profits under each of the two first-period strategies, we see that it is profitable for firm $B$ to win first-period sales if and only if

$$\beta_1 + (2N_2/N_1)\beta_2 > \alpha_1. \quad (1)$$

Next, suppose that $B$ does not have a sufficient cost advantage in the second period to guarantee that it will win the second-period competition (i.e., $-\alpha_2 \leq \beta_2$). In this case, network effects dominate cost differences. Whichever firm captures the first-period sales will make the second-period sales as well. First-period consumers realize that, as a group, they play a leadership role and their choice will be matched by second-period consumers. Firms also are aware that winning in the initial period is essential to making any sales, or profits, at all.

Conditional on winning the first-period sales, second-period profits are $N_2(\beta_2 + \alpha_2)$ for firm $A$ and $N_2(\beta_2 - \alpha_2)$ for firm $B$. Turning to the first period, we investigate the lowest first-period price that would be profitable for each technology. If firm $A$ loses the first-period competition, then it earns no profits in either period. If it wins the first-period sales at a price of $p_1$, firm $A$’s profits are

$$(p_1 - c_1)N_1 + (\beta_2 + \alpha_2)N_2. \quad (2)$$

Solving (2) for the price that yields zero profits, we obtain

$$p_1 = c_1 - (N_2/N_1)(\beta_2 + \alpha_2). \quad (3)$$

Similar calculations show that the minimal price at which firm $B$ would seek first-period sales is

$$q_1 = d_1 - (N_2/N_1)(\beta_2 - \alpha_2). \quad (4)$$

The firm that has the lower minimal price is the one that will serve all consumers in both periods. Comparing equations (3) and (4), we find that firm $B$ wins if and only if

$$N_1\alpha_1 + 2N_2\alpha_2 \leq 0. \quad (5)$$
Fig. 2. Equilibrium technology adoption under incompatibility

The equilibrium market outcome under incompatibility is illustrated in Fig. 2. As the asymmetry of the figure illustrates, there is a second-mover advantage among firms in the dynamic competition. Suppose that \(N_1 = N_2\), and that firm A’s initial cost advantage just equals firm B’s later advantage, i.e., \(0 < \alpha_1 = -\alpha_2\). As long as the cost differences are not too large, the market equilibrium entails all consumers purchasing technology B. The reason is that firm A cannot promise to price below cost in the second period, but firm B can price below cost in the first period.

It is straightforward to compute the firms’ profits and total welfare for each of the types of equilibria shown in Fig. 2. In Region #1, firm B wins in both periods, \(\pi^B = N_1(\beta_1 - \alpha_1) + N_2(\beta_2 - \alpha_2)\), \(\pi^A = 0\), and \(W = (N_1 + N_2)v(N_1 + N_2) - d_1N_1 - d_2N_2\). The same outcome and welfare arises in Region #2, but there firm A competes more strongly in the first period, and \(\pi^B = -\alpha_1N_1 - 2\alpha_2N_2\). In Region #3, the pattern of technology choice is A followed by B, \(\pi^A = N_1(\alpha_1 - \beta_1) - 2N_2\beta_2\), \(\pi^B = N_2(-\beta_2 - \alpha_2)\), and \(W = N_1(v(N_1) - c_1) + N_2(v(N_2) - d_2)\). Finally, in Region #4, firm A wins in both periods, \(\pi^A = \alpha_1N_1 - 2\alpha_2N_2\), \(\pi^B = 0\), and \(W = (N_1 + N_2)v(N_1 + N_2) - c_1N_1 - c_2N_2\).

\(^6\)We have more fully explored this and other biases in the market choice between incompatible technologies in Katz and Shapiro (1986).
C. Compatibility choice

When network externalities are large, the choice of whether to make the products or technologies compatible is one of the most important dimensions of industry performance. We assume that the decision to design a standardized interface linking the networks of the two firms’ products is made prior to production of the goods, i.e., before the period-one competition. By studying perfect equilibria, we are making the assumption that the firms accurately forecast industry competition with and without compatibility when making their compatibility decisions.

We denote by \( \Delta \pi \) the change in the firms’ joint profits in going from the incompatibility regime to the compatibility regime, gross of any costs of achieving compatibility. \( \Delta \pi \) measures the firms’ joint private incentives to achieve compatibility. A particular firm’s incentives are denoted by \( \Delta \pi^i \), \( i = A, B \). With obvious notation, the social incentive to achieve compatibility is given by \( \Delta W \). The difference between social and private incentives is given by the change in consumer surplus, \( \Delta S = \Delta W - \Delta \pi \). We say that a firm or a consumer cohort prefers compatibility if its payoff (weakly) rises on account of compatibility (before any costs associated with achieving compatibility are considered). Recall our labeling convention, \( \alpha_2 \leq 0 \).

Comparing the profits and consumer surplus in the two regimes, as calculated in Sections IIA and IIB above, one obtains:

**Proposition 1:** Firm A always prefers compatibility, as do second-period consumers. First-period consumers prefer compatibility if and only if technology B is sufficiently superior during period 2 that first-period consumers would be stranded if they chose technology A. Firm B may or may not prefer compatibility, but it’s interests always are opposed to those of consumers as a whole.

When \( \alpha_1 \), as well as \( \alpha_2 \), is nonpositive, firm A has higher production costs in both periods and earns zero profits under either compatibility regime. In the case where \( \alpha_1 > 0 \), firm A, the owner of the currently superior technology, prefers compatibility because this dampens its rival’s competitive zeal during the initial period. Compatibility removes the strategic linkages between the two periods of competition; since each firm’s competitive position in the second period is independent of who won the sales during the first period, neither firm is willing to set first-period price below cost. With compatibility, firm A can exploit its early cost advantage, independently of any future disadvantages it will face. Consumers are content to purchase A’s products without fear of being stranded with an obsolete model.

Figure 3 indicates the qualitative effects of compatibility on firm B, and on the firms jointly. The diagonally striped area in the Figure indicates those cost pairs \( (\alpha_1, \alpha_2) \) for which firm B prefers compatibility. Firm B tends to prefer compatibility if its cost disadvantage during the first period,
$a_1$, is large, or if its cost advantage during the second period, $-a_2$, is small. The shaded region corresponds to those cost pairs for which $\Delta \pi^B < 0$, but $\Delta \pi > 0$; the firms jointly gain from compatibility, although firm $B$ alone does not.

Firm $B$ always likes compatibility if it would lose the initial period competition without compatibility (Regions #3 and #4 from Figure 2). In these cases, compatibility makes the $B$ technology more attractive in period 2. But firm $B$ may prefer incompatibility if a lack of compatibility drives $A$ from the market or weakens $A$ as a competitor. In the case where technology $B$ has a cost advantage in both periods, firm $B$ always prefers incompatibility. More generally, a firm developing a new technology that will enjoy a sufficiently large cost advantage tomorrow (relative to its cost disadvantage today), has an incentive to design its products to be incompatible with the technology having lower costs today. Doing so cripples its rival’s ability to compete today, since first-period consumers know that they will be stranded tomorrow if they purchase the older technology with the early cost advantage.

Shifting attention to the demand side of the market, the effect of compatibility on consumers can be best understood by recognizing the following fact. Since the firms engage in pricing competition, consumers in a given period enjoy the surplus that the less well-placed firm can offer. That

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Footnote 7: This is analogous to our [1985] finding that a firm that is expected to have a large network prefers incompatibility.
surplus level determines how low a price is offered by the other firm, which actually makes the sales.

Because of this principle, second-period consumers always prefer compatibility. Compatibility increases the competitive position of the technology that did not prevail during the initial period; that technology is no longer handicapped by a smaller in-place base of units. Under compatibility, second-period consumers obtain the greatest surplus that they can hope to earn, \( v(N_1 + N_2) - c_2 \).

Turning to first-period consumers, if \(-\alpha_2 > \beta_2\), so that firm B will surely prevail in the second period, then these consumers prefer compatibility. Compatibility increases the size of A’s network and enhances the surplus that firm A can offer at price \( c_1 \), which is the lowest price that firm A will offer under either regime. If, however, \(-\alpha_2 \leq \beta_2\), then first-period sales determine second-period sales, and first-period consumers need not worry about being stranded. Therefore, they benefit from the intensified first-period competition to which incompatibility leads.

Given these incentives, we can now examine whether the firms will in fact achieve compatibility and how the social and private decisions compare. As we have seen, there are cases in which the move to compatibility increases the profits of firm A, yet reduces those of firm B. Thus, we must be careful to specify the process by which compatibility is achieved and whether side payments between the firms are feasible. We denote by \( F_i \) the costs that must be incurred by firm i if the two technologies are made compatible. \( F \) denotes total standardization costs for the industry; \( F^A + F^B = F \). We assume that compatibility does not alter the marginal costs of production.

When the firms are able to make side payments between each other, the private compatibility decision hinges on the sign of \( \Delta \pi - F \). The social decision rule is to achieve compatibility if and only if \( \Delta W \geq F \). Proposition 1 indicates that whenever firm B prefers incompatibility, the firms’ joint compatibility incentives are too low; \( \Delta \pi^B < 0 \) implies that \( \Delta S > 0 \) and, hence, that \( \Delta \pi < \Delta \pi^B + \Delta S = \Delta W \). The firms fail to achieve socially efficient compatibility when \( \Delta \pi < F < \Delta W \).

It is also possible that the firms have excessive incentives to achieve compatibility. Again by Proposition 1, they have excessive incentives whenever firm B prefers compatibility. When \( \Delta \pi > F > \Delta W \), the firms choose compatibility although its costs exceed the social benefits. The reason for these excessive incentives is the same as the reason why firm A prefers compatibility: compatibility leads to reduced competition during the first period (i.e., there is no below-cost pricing during the first period).

The result that the firms jointly have excess private compatibility incentives contrasts markedly with the usual results that firms would like to differentiate their products to relax competition.\(^8\) With compatibility the

\(^8\) Neven (1985) and Shaked and Sutton (1982) study the diminution of competition through product differentiation in a market without network externalities.
firms are selling perfect substitutes, while incompatible products are differentiated on the basis of network size. In the presence of network externalities, the firms diminish their rivalry in the initial period by producing perfect substitutes.

This result is analogous to the fact that firms may jointly prefer not to be able to make sunk capital investments in the context of dynamic rivalry. When capital investments (such as physical capital investments or advertising) are possible, each firm may have an incentive to overcapitalize in order to bolster its competitive position in the future. But the ability of all firms to make such investments may reduce the profits of each firm. In this analogy, increased compatibility corresponds to a reduced degree of sunkness of any such investments. If the investments are not sunk, they cannot constitute a form of commitment, and collective over-investment does not occur in equilibrium. Likewise, with compatibility each of the firms is unwilling to sustain loses during the early stages of competition.

When side payments are not feasible, and the firms disagree on the desirability of making their products compatible, it is important to specify whether unilateral standardization is feasible, or if decisions must be made jointly. Both cases may arise in practice. Often, a single firm can act unilaterally to make its product compatible with those of another firm by constructing an adapter. For example, some video game manufacturers have developed physical adapters that allow their machines to run games initially written for their competitors' hardware. Similarly, one firm may be able unilaterally to adopt another network’s specifications for its product design. An example of this pattern is the manufacture by several companies of personal computers that are sufficiently similar to the IBM PC that they can run software written for the IBM PC.

In other cases, compatibility is attainable only through the joint adoption of a product standard; the firms must act together to make their products compatible. These cases arise when the interface or product design is proprietary or when an adapter is prohibitively expensive (e.g., equal to the cost of the product itself). The CPM operating system for personal computers and the broadcast television standards are both examples of jointly adopted standards.9

When a single firm is able unilaterally to construct an adapter, the adapting firm bears all of the compatibility costs, \( F \). An adapter will be built if and only if \( \Delta \pi' \geq F \) for at least one of the two firms. Proposition 1 establishes that firm \( A \) will find it profitable to construct an adapter if \( F \) is sufficiently small. In other words, we find that the owner of an older

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9 In a variety of manufacturing industries, standards are promulgated to encourage compatibility. The American National Standards Institute establishes domestic standards and represents the U.S. in the International Organization for Standardization. Carlton and Klamer (1983) discuss compatibility in telephony, as well as in the electronic funds transfer and rail transportation industries.
technology will make an effort to become compatible with future technologies. Yet the newer technology may resist designing its product to be compatible with the older technology. If the firm controlling the emerging technology does construct an adapter, then we know that consumers, in particular first-period consumers, are made worse off as a result. This result may appear to be an odd one, but is is not hard to understand. Firm B constructs the adapter in those cases where the dominant effect of compatibility is to dampen first-period competition.

For an industry standard to be established, the firms must act together. Compatibility will be achieved if and only if $\Delta \pi^t \geq F^t$ for both firms. Hence, compatibility can arise only if firm B, the emerging technology, consents, in which case (by Proposition 1) consumers as a whole must be made worse off. If $\Delta \pi < \Delta W$, then $\Delta \pi^B < 0$ and firm B will block what may be efficient compatibility. This result is not surprising given our earlier analysis of side payments; the private compatibility rule when the compatibility mechanism is an industry standard is more stringent absent side payments than it is when side payments are feasible. Of course, when firm B likes standardization, the firms' joint incentives are excessive, and side payments may allow firm B to bribe firm A (perhaps by covering the bulk of the standardization costs) in order to bring about standards that are socially inefficient.\textsuperscript{10}

### III. Network competition with uncertain technological progress

Often, consumers and firms are uncertain about the future costs of the competing technologies. In this section, we consider a market in which the second-period costs of the two technologies are unknown in the first period. As we have seen, given our assumption that demand is inelastic in each period, the market equilibrium depends only on the difference in second-period costs, $\alpha_2$. Let $f(\cdot)$ denote the density function of $\alpha_2$. We assume that all agents know this distribution of the cost difference. For simplicity, we assume that the two firms have identical first-period costs, i.e., $\alpha_1 = 0$.

#### A. Equilibrium with compatible products

Suppose that the two products are compatible. For any given realization of $\alpha_2$, the second-period outcome is determined as in our earlier case where the second-period costs were known with certainty in the first period. Taking expectations over the possible realizations of $\alpha_2$, the expected second-period profits of firm A are

$$N_2 \int_0^{\alpha_0} \alpha_2 f(\alpha_2) \, d\alpha_2.$$  \hspace{1cm} (6)

\textsuperscript{10} An example would be: $\Delta W < F < \Delta \pi$, $\Delta \pi^A < F^A$, and $\Delta \pi^B > F^B$. 

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Similarly, the expected second-period profits of firm $B$ are

$$N_2 \int_{-\infty}^{0} -\alpha_2 f(\alpha_2) \, d\alpha_2. \tag{7}$$

The outcome in the first period has no effect on second-period profits, and as before competition in the first period is essentially a single-period Nash-Bertrand pricing game. Thus, the equilibrium price in the first period is $p_1 = c_1 = d_1 = q_1$, and the firms earn zero profits in that period. Thus, the firms’ total profits over the two periods are given by equations (6) and (7).

B. Equilibrium with incompatible products

As we have shown in Section II, for any given realization of $\alpha_2$, first-period sales enter into the calculation of the second-period outcome when the products are incompatible. Let $R_i$ denote firm $i$’s expected second-period profits conditional on its having won all of the first-period sales, and let $L_i$ denote expected second-period profits conditional on having made no first-period sales. Integrating over the relevant regions, we obtain

$$R^A = N_2 \int_{-\beta_2}^{\infty} \{\alpha_2 + \beta_2\} f(\alpha_2) \, d\alpha_2 \tag{8}$$

and

$$L^A = N_2 \int_{\beta_2}^{\infty} \{\alpha_2 - \beta_2\} f(\alpha_2) \, d\alpha_2. \tag{9}$$

The difference between the expected profits conditional on winning and losing first-period sales tells us the maximal amount that firm $A$ would be willing to pay to obtain the first-period sales (i.e., how much the firm would be willing to subsidize first-period consumers). Letting $M^A$ denote this difference, $R^A - L^A$, we have

$$M^A = N_2 \beta_2 \left\{ \int_{\beta_2}^{\infty} f(\alpha_2) \, d\alpha_2 + \int_{-\beta_2}^{\infty} f(\alpha_2) \, d\alpha_2 \right\} + N_2 \int_{-\beta_2}^{\beta_2} \alpha_2 f(\alpha_2) \, d\alpha_2. \tag{10}$$

Similar calculations show that firm $B$’s maximal willingness to subsidize first-period consumers is

$$M^B = N_2 \beta_2 \left\{ \int_{-\infty}^{-\beta_2} f(\alpha_2) \, d\alpha_2 + \int_{-\beta_2}^{\beta_2} f(\alpha_2) \, d\alpha_2 \right\} - N_2 \int_{-\beta_2}^{\beta_2} \alpha_2 f(\alpha_2) \, d\alpha_2. \tag{11}$$

In setting its first-period price, firm $A$ is willing to go as low as $c_1 - M^A/N_1$. Firm $B$ is willing to go as low as $d_1 - M^B/N_1$. Consumers choose the firm from whom expected surplus is greater.

C. Compatibility choice

The general case of uncertain technological progress is difficult to analyze. There are, however, two important special cases where we can characterize
the compatibility incentives fully. First, suppose that \( f(\cdot) \) is symmetric around 0, i.e., that the firms are ex ante symmetrically placed. In this case, the expressions for \( M^A \) and \( M^B \) simplify greatly. Since

\[
\int_{-\infty}^{\infty} f(\alpha_2) \, d\alpha_2 = \int_{-\infty}^{-\beta_2} f(\alpha_2) \, d\alpha_2 \quad \text{and} \quad \int_{-\infty}^{\infty} f(\alpha_2) \, d\alpha_2 = 1,
\]

we have \( M^A = N_2 \beta_2 = M^B \). Hence, the first-period equilibrium price is \( c_1 - \beta_2 (N_2/N_1) \), because each firm is willing to pay up to \( N_2 \beta_2 \) to win the first-period sales. Total expected profits for firm \( i \) thus are equal to

\[
L^A = N_2 \int_{-\beta_2}^{\infty} (\alpha_2 - \beta_2) f(\alpha_2) \, d\alpha_2.
\]

Comparing equations (6) and (12), and using the fact that the two firms earn equal expected profits, we find that compatibility raises expected profits.\(^\text{11}\)

The reason why symmetrically placed firms always prefer compatibility is similar to the incentives noted in the certainty model of Section II. In the second period, the firms are asymmetric (with or without compatibility) and competition does not fully dissipate profits. With incompatible products, however, competition in the first period strongly tends to dissipate second-period profits; they earn combined losses in the first period absent compatibility. With incompatibility, the firms each earn the “loser’s” level of expected second-period profits, i.e., the profits earned by a firm with an installed base disadvantage. Under compatibility, there is no scope for installed base investment, and second-period profits are not dissipated in the first period. Thus, in our uncertainty model, the firms want to reduce ex ante competition, which occurs while they are in a symmetric position.

Summarizing the effects of compatibility on consumers as well as firms:

**Proposition 2:** Suppose that the firms are ex ante symmetric. Then compatibility raises expected profits. For any realization of \( \alpha_2 \), compatibility raises or leaves unchanged second-period consumer surplus and total welfare. If \( N_1 \beta_1 \leq N_2 \beta_2 \), then for any realization of \( \alpha_2 \), compatibility lowers first-period consumer surplus and total consumer surplus.

**Proof** The result for profits is established above. Total welfare reaches its maximum under compatibility, since each consumer enjoys gross benefits of \( v(N_1 + N_2) \) and the cheaper technology is produced in each period. Second-period consumers must benefit from compatibility by Proposition 1. The final part of the proposition is established by direct computation. Q.E.D.

\(^{11}\) For particular realizations of \( \alpha_2 \), however, ex post industry profits would have been higher had the products not been compatible. One such case arises when the firm that wins first-period sales is the one with higher second-period costs and \( \beta_2 - |\alpha_2| < |\alpha_2| \).
Given ex ante symmetry, first-period consumers and consumers as a whole will prefer incompatibility if the realized cost advantage of the firm that lost in the first period is less than \( \beta_2 \). In such cases, de facto standardization arises even absent compatibility, and first-period consumers benefit from the increased competition to serve them under incompatibility. If, however, the firm that wins the first-period sales has much higher costs in the second period, then first-period consumers will be stranded. In this case, they must compare the network benefits that arise from compatibility, \( N_1\beta_1 \), with the loss of their subsidy from below-cost pricing, \( N_2\beta_2 \). When \( N_1\beta_1 < N_2\beta_2 \), the subsidy is worth more than is the larger network, and these consumers prefer incompatibility, despite stranding.

Now consider a second special case in which \( \alpha_2 \) always lies within the interval \([-\beta_2, \beta_2]\), although the firms need not be ex ante symmetric. In this case, whichever firm wins the first-period sales also wins the second. Hence, \( L' = 0 \), and

\[
M^A = N_2 \int_{-\beta_2}^{\beta_2} (\alpha_2 + \beta_2) f(\alpha_2) \, d\alpha_2.
\]

\[
= N_2 \{ \bar{\alpha}_2 + \beta_2 \}, \tag{13}
\]

where \( \bar{\alpha}_2 \) is the mean of \( \alpha_2 \). Similarly, \( M^B = N_2 \{ -\bar{\alpha}_2 + \beta_2 \} \). Given the labeling convention that \( \bar{\alpha}_2 \leq 0 \), \( M^B \geq M^A \), and firm B “outbids” firm A for first-period sales. Firm B earns total profits of

\[
M^B - M^A = -2N_2\bar{\alpha}_2. \tag{14}
\]

Comparing the sum of equations (6) and (7) with equation (14), making straightforward algebraic manipulations, and applying Proposition 1 to the effects of compatibility on consumers, we obtain

**Proposition 3:** Suppose that the support of \( \alpha_2 \) lies within the interval \([-\beta_2, \beta_2]\) and that the mean of \( \alpha_2 \) is nonpositive. Then first-period consumers prefer incompatibility, and second-period consumers prefer compatibility for any realization of \( \alpha_2 \). The firms’ expected profits under compatibility exceed expected profits under incompatibility if

\[
0 \leq E[\Delta \pi] = N_2 \left\{ 3 \int_0^{\beta_2} \alpha_2 f(\alpha_2) \, d\alpha_2 + \int_{-\beta_2}^0 \alpha_2 f(\alpha_2) \, d\alpha_2 \right\}. \tag{15}
\]

Welfare attains its first-best level under compatibility, and thus compatibility cannot lower total surplus. In fact, it may strictly raise welfare. Since consumers match across periods, the full network benefits are realized in either case, and any welfare gains must come on the production side of the market. Under compatibility, production costs are minimized. But under incompatibility, firm B will have positive second period sales (given that it has won the first-period sales) even when it is the higher-cost
producer. Hence, compatibility raises expected welfare by

\[ E[\Delta W] = N_2 \int_0^{\beta_2} \alpha_2 f(\alpha_2) \, d\alpha_2 > 0. \]  \hspace{1cm} (16)

Using the definition of total surplus, equations (15) and (16) imply that the expected change in total consumer surplus from the move to compatibility is

\[ E[\Delta S] = -N_2 \left\{ \int_0^{\beta_2} 2\alpha_2 f(\alpha_2) \, d\alpha_2 + \int_{-\beta_2}^0 \alpha_2 f(\alpha_2) \, d\alpha_2 \right\}. \]  \hspace{1cm} (17)

The right-hand side of equation (17) may be either positive or negative. Note that \( E[\Delta W] > 0 \) implies that whenever \( E[\Delta \pi] < 0, E[\Delta S] > 0 \); when the firms jointly oppose compatibility, consumer always collectively favor it.

Equation (15) suggests that the firms collectively prefer compatibility as long as they have similar expected second-period costs. When \( \alpha_2 = 0 \), for example,

\[ \int_{-\beta_2}^0 -\alpha_2 f(\alpha_2) \, d\alpha_2 = \int_0^{\beta_2} \alpha_2 f(\alpha_2) \, d\alpha_2, \]

and the right-hand side of equation (15) is positive; the firms prefer compatibility. The competition to obtain installed base is strongest when the firms are evenly matched ex ante. At the other extreme, if \( \alpha_2 \) is always negative, then the right-hand side of equation (15) is negative, and the firms, in particular firm \( B \), prefer incompatibility. This result generalizes our earlier finding in the certainty case that a firm prefers incompatibility if it enjoys a cost advantage at each date.

Proposition 3 compares total profits under the two compatibility regimes. Given that \( \pi^A = 0 \) under incompatibility, clearly \( \Delta \pi^A \geq 0 \). Since

\[ \Delta \pi^B = 2N_2 \int_0^{\beta_2} \alpha_2 f(\alpha_2) \, d\alpha_2 + N_2 \int_{-\beta_2}^0 \alpha_2 f(\alpha_2) \, d\alpha_2, \]  \hspace{1cm} (18)

which may be positive or negative, firm \( B \)'s attitude towards compatibility is more sensitive to the distribution of \( \alpha_2 \). For \( \bar{\alpha}_2 = 0 \), \( \Delta \pi^B > 0 \), and the firms both prefer compatibility.

In addition to examining the effects of changes in \( \bar{\alpha}_2 \), we can examine the incentive effects of a mean-preserving spread in the distribution of \( \alpha_2 \).

**Corollary:** Suppose that \( \alpha_2 \) lies within the interval \([-\beta_2, \beta_2]\) and the mean of \( \alpha_2 \) is nonpositive. Then a mean preserving spread in the distribution of \( \alpha_2 \) increases the firms' collective incentives to achieve compatibility.\(^{12}\)

**Proof** Rewriting equation (15),

\[ E[\Delta \pi] = N_2 \int_0^{\beta_2} \alpha_2 f(\alpha_2) \, d\alpha_2 + N_2 \int_{-\beta_2}^0 -\alpha_2 f(\alpha_2) \, d\alpha_2 + 2N_2 \bar{\alpha}_2. \]  \hspace{1cm} (19)

\(^{12}\) We assume the spread does not expand the support of \( \alpha_2 \) beyond \([-\beta_2, \beta_2]\).
Of course, $\tilde{\alpha}_2$ is unaffected by a mean preserving spread. The mean preserving spread must, however, raise (or leave unchanged) the first integral on the right-hand side of the equation since this integral is taken over a tail (the mean of $\alpha_2$ is nonpositive). Since the first integral rises, 

$$\int_{-\beta_2}^{0} \alpha_2 f(\alpha_2) \, d\alpha_2 = \tilde{\alpha}_2 - \int_{0}^{\beta_2} \alpha_2 f(\alpha_2) \, d\alpha_2$$

must fall. Thus, the second right-hand side integral must rise. This fact implies that the mean-preserving spread raises the right-hand side of equation (19). Q.E.D.

A mean-preserving spread in $\alpha_2$ may be interpreted as a change in the correlation between the two firms' second-period costs. See, for example, the two panels of Fig. 4, in each of which $(c_2, d_2)$ is distributed over the

**Fig. 4.** Positively and negatively correlated $c_2$ and $d_2$
shaded region. The shaded regions in Figs 4a and 4b are assumed to have the same center of mass. In Fig. 4a, $c_2$ and $d_2$ are highly correlated, and their difference, $\alpha_2$, exhibits little spread. In Fig. 4b, the two firms' costs are less correlated; the corresponding distribution of $\alpha_2$ is a mean-preserving spread of the distribution from Fig. 4a. Therefore, the Corollary suggests that the firms are more likely to prefer compatibility when their second-period costs are uncorrelated or negatively correlated. It is exactly in such circumstances that compatibility generates the greatest social benefits.

In closing this section, we should note that one could use Propositions 2 and 3 to analyze the compatibility decision, as in Section II. The same basic forces that may lead to insufficient or excessive private compatibility incentives remain present in the uncertainty case.

IV. Conclusion

Our analysis demonstrates that the social and private incentives to achieve compatibility may diverge. The most striking result is that firms may use product compatibility as a means of reducing competition among themselves. By choosing compatible technologies, the firms prevent themselves from going through an early phase of extremely intense competition where each firm tries to build up its network to get ahead of its rival. As a result, product compatibility tends to lower the surplus of first-period consumers, and the firms' compatibility incentives may be socially excessive. The private incentives are not always excessive, however. Product compatibility tends to strengthen second-period competition since no firm falls behind in terms of its first-period installed base. Thus, second-period consumers derive greater surplus under compatibility than under incompatibility, and the firms' compatibility incentives may be too low.

There are several directions in which it would be useful to extend our analysis. One would be to endogenize the rate of technological progress. Obviously, such an extension would raise a host of interesting and difficult issues. For example, how might firms commit themselves to vigorous R&D activities in the future as a way of building a base today?

A second extension would be to consider elastic demands. By assuming that demand is perfectly inelastic over the relevant range, we have assumed away one motivation for below-cost pricing during the first period. If the firms produce compatible products and demands are inelastic, neither firm is willing to set its first-period price below cost. With elastic demand, however, low first-period prices can help second-period profits even under compatibility. The reason is that the quantity purchased at a given price will be an increasing function of the network size, and second-period profits for the winning firm are equal to $|\alpha_2|$ times the number of units demanded at $\max \{c_2, d_2\}$.\textsuperscript{13} Of course, in the first period each firm is uncertain as to

\textsuperscript{13} Here, we are assuming that the monopoly price given costs of $\min \{c_2, d_2\}$ is more than $\max \{c_2, d_2\}$.
whether it will make second-period sales; expanding the network base may merely be helping its rival. Thus, there is a free-rider problem. But as long as a firm's chance of having the lower second-period cost is positive, it will have incentives to set price in the first period below costs to win the sales.\footnote{Another consequence of elastic demand is that compatibility, by strengthening second-period competition, represents a commitment to lower second-period prices, and thus shifts \textit{first-period} demand outwards.}

Although elastic demand introduces a number of additional effects, the fundamental forces that we have identified in the simple model above clearly remain.

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