Technology Adoption in the Presence of Network Externalities

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We analyze technology adoption in industries where network externalities are significant. The pattern of adoption depends on whether technologies are sponsored. A sponsor is an entity that has property rights to the technology and hence is willing to make investments to promote it. Key findings include the following: (1) compatibility tends to be undersupplied by the market, but excessive standardization can occur; (2) in the absence of sponsors, the technology superior *today* has a strategic advantage and is likely to dominate the market; (3) when one of two rival technologies is sponsored, that technology has a strategic advantage and may be adopted even if it is inferior; (4) when two competing technologies both are sponsored, the technology that will be superior *tomorrow* has a strategic advantage.

I. Introduction

The benefit that a consumer derives from the use of a good often depends on the number of other consumers purchasing compatible items. Consider, for example, the owner of a videocassette recorder (VCR). At present, there are two competing technologies, beta and VHS. These technologies are incompatible with one another; cassettes produced for use on one type of VCR cannot be played on the other type. Because of the increasing returns to scale in the provision of the complementary good (rental services of prerecorded cassettes),

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the owner of a VCR will find a greater variety of programming available for his machine if more VCRs are sold using his technology. He also benefits from the ability to exchange cassettes with other users of compatible machines and from superior service that may be available for the VCR technology with the larger in-place base of machines. We call these positive external consumption benefits "network externalities."

Network externalities are significant in many important industries. They have long been recognized in the context of physical networks such as the telephone and railroad industries.[1] Most examples of network externalities entail the provision of a durable good and a complementary good or service. In the computer industry, software and hardware must be used together. The question of compatibility is whether different brands or technologies of the durable good (e.g., hardware) can utilize identical units of the complementary good (e.g., software). In the communications area, all television sets are compatible (i.e., they receive and process the same signals), but incompatible AM stereo technologies are currently competing for survival. In 1950, the Federal Communications Commission (FCC) adopted a color television system that was incompatible with the existing black and white system, although production soon was stopped by an order by the Director of Defense Mobilization.[2] Currently, there is a policy debate over standards for the emerging technology of high-definition television. Any technology requiring specific training is subject to network externalities: the training is more valuable if the associated technology is more widely adopted.

When network externalities are significant, so too are the benefits of having compatible products. There are two ways in which compatibility may be achieved. First, even products utilizing different technologies may be designed to work with one another. For example, the use of standardized interfaces allows a variety of components in a personal computer system to be used together; several different brands of personal computer may utilize a given brand of printer. In a variety of manufacturing industries, industrywide standards are designed to encourage compatibility.[3] Of course, producing compatible designs requires interfirm cooperation and may raise production costs. In Katz and Shapiro (1985, 1986), we study the private and social incentives to achieve technical compatibility, or standardization.

[1] Carlton and Klamer (1983) discuss compatibility in these industries as well as in the electronic funds transfer industry. Rohlfs (1974) and Oren and Smith (1981) analyze network externalities in the context of a monopoly telecommunications network.

[2] We are grateful to Stanley Besen for bringing this example to our attention.

[3] The American National Standards Institute establishes domestic standards and represents the United States in the International Organization for Standardization.

For some products (e.g., VCRs), the competing technologies may be inherently incompatible. In such cases, there is another way to enjoy the full benefits of network externalities: 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-by-sheer-force-of-numbers.[4] The costs of this type of standardization may be twofold. First, there may be a loss of variety, reducing the flow of services generated by the product. Computer users, for example, point out that Apple computers, while incompatible with IBM machines, perform a number of tasks that IBM-compatible machines cannot. These services would be lost if only IBM-compatible technologies were manufactured and consumed. Second, the costs of each technology may vary across consumers, so that, if only one technology is offered, some consumers are forced to purchase what is for them the more expensive technology. Cost differences across consumers are commonplace when there is technological progress and consumers purchase at different dates.

In this paper, we study the dynamics of industry evolution in a market with technological change where there are two inherently incompatible technologies subject to network externalities. Network externalities have two fundamental effects on the dynamics of industry evolution. First, the relative attractiveness today of rival technologies is influenced by their sales histories. In effect, there are "demand-side economies of scale"; a given product is more attractive the larger is the in-place base of consumers using that product. Second, and perhaps more important, in the presence of network externalities, a consumer in the market today also cares about the *future* success of the competing products. As long as the good is durable (or there is technology-specific human capital investment), the total benefits derived from it will depend, in part, on the number of consumers who adopt compatible products in the future.

Network externalities share the first type of increasing return to scale with learning by doing.[5] The second source of demand-side scale economies is, however, peculiar to industries with network externalities. As a result of these two effects, the dynamics of industries subject to network externalities are fundamentally different from those of conventional industries.

We examine two basic questions regarding the process of industry evolution: (1) Will the market achieve de facto standardization? (2)

[4] David (1985) provides a very entertaining description of how the QWERTY standard was adopted.

[5] Arthur (1985) analyzes technology choice in the presence of embodied technical progress, i.e., learning by doing.

When the market does choose a standard, is the choice the socially optimal one? The answers to these questions depend on whether there are well-defined property rights to the technologies.

In the absence of well-defined property rights, free entry into the supply of a technology will lead to marginal cost pricing.[6] In the light of the external benefits, one would expect the competitive equilibrium to be inefficient, and our formal results confirm this intuition. Distortions arise because each consumer ignores the network effects on other consumers when making his consumption decision. Hence, the market is biased toward nonstandardization. When standardization does occur, the wrong standard may be chosen. Our analysis supports the conventional view that the technology that is superior today has a strategic, first-mover advantage: it can become locked in as the standard.

If a single firm controls the property rights to a given technology or if there are other entry barriers into the supply of that technology, then a supplier will be willing to make investments in the form of penetration pricing to establish the technology because such investments can later be recouped by pricing in excess of marginal costs. We call such a firm a "sponsor." In the VCR industry, each of the two competing technologies is sponsored because patent protection prevents free entry into the VCR market. In the typewriter industry, on the other hand, property rights to specific keyboard designs were not established, and there were no sponsors in our sense of the term.

Sponsorship can internalize some of the externalities through below-cost pricing at the beginning of a technology's life. But sponsorship can create problems of its own. When one technology is sponsored and the other is not, the sponsored technology tends to be adopted too much. The market outcome still may entail splitting in cases in which standardization is socially optimal. But the market outcome also may entail excessive standardization or standardization on the wrong technology. In fact, we find that a sponsored technology may dominate the market even when *all* consumers agree that a rival, nonsponsored technology is superior.

For the case of two sponsors, the most dramatic effect of sponsorship is that a second-mover advantage arises. The technology that will be superior tomorrow has a strategic advantage. If consumers are forward looking (i.e., form rational expectations about future sales), we obtain exactly the opposite of the view that industries become locked in to older, inferior technologies. In a sense, the market exhibits "excessive foresight."

[6] Farrell and Saloner (1985) study the evolution of an industry in which one technology initially has been adopted and neither technology is proprietary.

In the following section we outline our formal model. In Section III we study the pattern of adoption that would be induced if a welfare maximizer chose all prices. The bulk of our analysis is in Section IV, where we describe market equilibria for several different patterns of sponsorship and compare the market outcomes with the socially optimal ones. Section V discusses the time consistency constraint faced by firms in our model and is followed by a brief discussion of the directions in which to extend the analysis.

II. Technology Choice by Consumers

We first develop the demand side of a simple model of technology choice in the presence of network externalities. We show how consumers respond to a given time path of prices. The model is kept as simple as possible in order to focus most clearly on the effects of network externalities and sponsorship.

There are two time periods, or generations of consumers, $t = 1, 2$, with N_t consumers in period t. A period t consumer has a completely inelastic demand for one unit of the good in period t. There are two technologies, A and B, from which to choose. The prices of technologies A and B in period t are denoted by p_t and q_t, respectively. In this section we take all prices as known and exogenously given. Let δ_t denote the discount for technology B (relative to technology A) during period t: $\delta_t \equiv p_t - q_t$.

The benefits that a consumer derives from consumption of one unit of the good depend on how many other consumers ultimately purchase compatible units, that is, units utilizing the same technology. In other words, the extent of consumption externalities depends only on the final network sizes. Let x_t and y_t denote the quantities of technologies A and B, respectively, that are sold in period t. Given our assumption that all period t consumers make purchases, $y_t = N_t - x_t$. A consumer who purchases technology A in period t derives gross benefits of $v(x_1 + x_2)$ and net benefits (or surplus) of $v(x_1 + x_2) - p_t$. The corresponding values for a consumer who purchases technology B in period t are $v(y_1 + y_2)$ and $v(y_1 + y_2) - q_t$.[7] By having gross consumption benefits depend only on the number of consumers purchasing the *same* technology, we are assuming that the two technologies are incompatible. Consumers in our model are homogeneous in that all of them have the same benefit function $v(\cdot)$.

First-period consumers rationally forecast second-period sales in order to make their purchase decisions. First-period consumers rec-

[7] As we shall see, allowing first-period consumers to derive intermediate benefits, i.e., have benefit functions of the form $u(x_1) + v(x_1 + x_2)$, would not change our results.

ognize that the consumption decisions of second-period buyers must be optimal given the pattern of first-period purchases (i.e., we look for a perfect equilibrium). Hence, we begin our analysis by considering the purchasing decisions of the N_2 consumers who choose technologies in period 2. We look for a Nash equilibrium in second-period technology choices, where each second-period consumer makes his technology choice taking the purchasing decisions of all other (first- and second-period) consumers as given. For a network to have positive second-period sales in equilibrium it must be the case that no consumer purchasing that technology wants to switch to the other technology. For technology A, this condition is $v(x_1 + x_2) - p_2 \geq v(y_1 + y_2 + 1) - q_2$, or $v(x_1 + x_2) - v(y_1 + y_2 + 1) \geq \delta_2$. For technology B, the condition is $v(x_1 + x_2 + 1) - v(y_1 + y_2) \leq \delta_2$.

Given that $v(\cdot)$ is an increasing function, these two conditions cannot be satisfied simultaneously. Therefore, one technology or the other will dominate in the second period: either $x_2 = 0$ or $x_2 = N_2$.[8] A similar argument shows that all first-period consumers will purchase the same technology as one another.[9]

Suppose that all of the first-period consumers have chosen technology A. Then an equilibrium exists in which all second-period consumers choose A if and only if $v(N_1 + N_2) - v(1) \geq \delta_2$. An equilibrium exists with all second-period consumers purchasing technology B if and only if $v(N_1 + 1) - v(N_2) \leq \delta_2$. These last two inequalities may be satisfied simultaneously.

Given that all period 2 consumers are identical, they will agree on which outcome yields higher consumer surplus. We assume that, when there are multiple equilibria, consumers buying in the same period can coordinate their purchase decisions to choose the outcome that is Pareto preferred. When the two outcomes are compared, second-period consumers will match first-period consumers and adopt technology A if and only if

$$v_b - v_2 \geq \delta_2, \tag{1}$$

where we have adopted the notation $v_b \equiv v(N_1 + N_2)$, with b for both, and $v_t \equiv v(N_t)$, $t = 1, 2$. The second-period outcome depends on a comparison of technology A's installed-base advantage, $v_b - v_2$, and technology B's price advantage, δ_2.

[8] If consumers ignored their influence on network size (i.e., if there were a continuum of consumers), then an unstable interior equilibrium might exist. Of course, our strong within-period bandwagon results rely on consumer homogeneity.

[9] It is for this reason that intermediate benefits do not alter the analysis. They would not affect the comparison between technologies since the intermediate benefits would be $v(N_1)$ in all cases. Allowing for intermediate benefits only strengthens the tendency of first-period consumers to cluster on one technology.

It can be shown in a similar fashion that, if first-period consumers all choose technology B, the second-period consumers will match if and only if

$$v_b - v_2 \geq -\delta_2. \tag{2}$$

Now consider first-period consumers. Each first-period consumer makes his technology choice taking the purchase decisions of other first-period consumers as given and having calculated the resulting second-period equilibrium purchasing decisions. If inequalities (1) and (2) both hold, that is, $|\delta_2| \leq v_b - v_2$, then first-period consumers know that, no matter which technology they choose, second-period consumers will follow. In this case, first-period consumers choose the standard by comparing $v_b - p_1$ and $v_b - q_1$. Technology A will be chosen if and only if $p_1 \leq q_1$, that is, $\delta_1 \leq 0$.

When (1) holds but (2) does not, that is, $\delta_2 < v_2 - v_b$, second-period consumers will purchase technology A no matter what first-period consumers choose to do. Thus first-period consumers compare $v_b - v_1$ with δ_1. Finally, when (1) is violated but (2) holds, that is, $\delta_2 > v_b - v_2$, second-period consumers will choose technology B no matter what first-period consumers do. In this case, first-period consumers compare $v_1 - v_b$ with δ_1. Figure 1 graphs the consumer equilibrium as a function of the price differences, δ_1 and δ_2. The notation AB in a region of the figure, for example, indicates that first-period consumers adopt technology A and second-period consumers choose technology B if δ_1 and δ_2 lie in the relevant region.

III. Second-best Pricing

We turn now to an analysis of the socially optimal price paths for the two technologies. We take total surplus as our welfare measure.[10] If a perfectly informed central planner had the power to order any given consumer to choose a particular technology, then there would be cases in which it would be socially optimal to have consumers making purchases within a single period choose different technologies.[11] We consider a more limited planner who can set prices in each period (using taxes and subsidies) but cannot mandate adoption. The analy-

[10] We do not address the interesting question whether an actual planner would, in fact, maximize total surplus. One might expect that the government would instead serve only the current generation of voters.

[11] For example, suppose that technology B is prohibitively expensive in period 1 but is cheaper in period 2. It may be socially optimal for most period 2 consumers to use B but for some to use A in order to increase the period 1 consumers' benefits. This pattern of splitting is most likely to be optimal if $N_2 > N_1$ and if there is a threshold network size (larger than N_1) at which $v(\cdot)$ increases sharply.

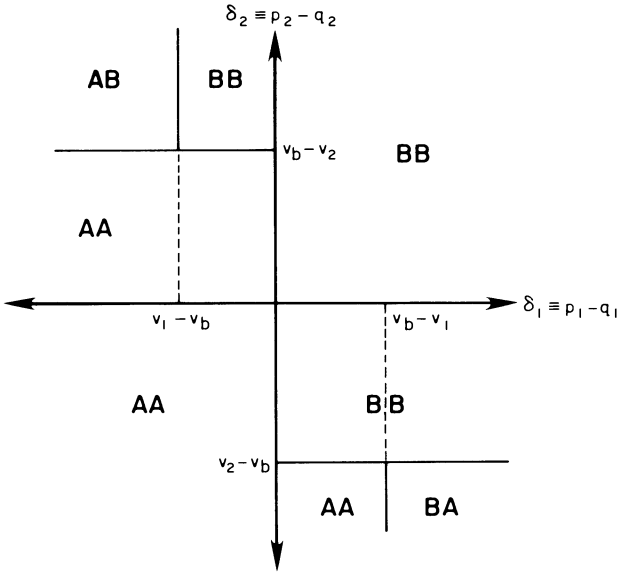

FIG. 1.—Technology choice by consumers

sis of the previous section shows that such a planner is restricted to choosing a single technology for all the consumers in any one period.

When consumers all agree on which technology is better (i.e., cheaper), then clearly the optimum entails all consumers adopting that technology. When the relative costs of the two technologies shift over time, one must compare the production cost savings of heterogeneous products with the loss of network externalities in deciding whether to standardize. Let c_t and d_t denote the constant marginal costs of technologies A and B, respectively, in period t. The costs are taken to be exogenously given and known to all agents. Let Δ_t denote technology B's cost advantage at time t: $\Delta_t \equiv c_t - d_t$.

Consider the case in which technology A is cheaper than B in the first period but more expensive in the second period: $\Delta_1 < 0$ and $\Delta_2 > 0$. It is useful to think of technology B as the newer technology; initially it is more expensive, but in time it overtakes its older rival. There are three outcomes to compare. Let W_{AB} denote the total surplus level that obtains when first-period consumers purchase technology A and second-period consumers purchase technology B. Define W_{AA} and W_{BB} analogously. We then have

$$W_{AA} = (N_1 + N_2)v_b - c_1N_1 - c_2N_2, \tag{3}$$

$$W_{BB} = (N_1 + N_2)v_b - d_1N_1 - d_2N_2, \tag{4}$$

$$W_{AB} = N_1v_1 + N_2v_2 - c_1N_1 - d_2N_2. \tag{5}$$

If all consumers purchase the same technology, the network benefits are identical whether the purchase pattern is AA or BB. The socially optimal decision is made on the basis of which technology is cheaper on average:

$$W_{BB} - W_{AA} = \Delta_1 N_1 + \Delta_2 N_2. \tag{6}$$

Suppose that $W_{AA} > W_{BB}$. There still is a question whether it is socially optimal to split consumers across the two technologies. Subtracting equation (5) from equation (3) yields

$$W_{AA} - W_{AB} = (N_1 + N_2)v_b - (N_1 v_1 + N_2 v_2) + d_2 N_2 - c_2 N_2.$$

Hence W_{AA} is greater than W_{AB} if and only if

$$\left(\frac{N_1}{N_2}\right)(v_b - v_1) + (v_b - v_2) > \Delta_2. \tag{7}$$

The right-hand side of (7) is the period 2 per capita advantage of splitting consumers across technologies—second-period consumers can purchase the technology that is cheaper at that time. The left-hand side of (7) measures the disadvantage of splitting—consumers are divided between incompatible technologies, reducing the extent to which the network externalities are enjoyed.

A similar line of argument shows that $W_{BB} > W_{AB}$ if and only if

$$\left(\frac{N_2}{N_1}\right)(v_b - v_2) + (v_b - v_1) > -\Delta_1. \tag{8}$$

Recall that Δ_1 is negative.

When the cost difference between the two technologies is near zero in at least one period, at least one of inequalities (7) and (8) is satisfied, and standardization is socially optimal. When the cost differences are large in both periods, splitting is optimal. Figure 2 illustrates the socially optimal outcome for all possible values of Δ_1 and Δ_2. In drawing figure 2, we have made use of the fact that the social problem is completely symmetric. The same type of analysis that we have applied to $\Delta_1 < 0$ and $\Delta_2 > 0$ also holds for the case in which $\Delta_1 > 0$ and $\Delta_2 < 0$.

IV. Industry Evolution and Technology Sponsorship

A. *Unsponsored Technologies*

We turn now to examination of the market outcome. Initially, we consider the case of competition between unsponsored technologies. In other words, there is free entry into the supply of products em-

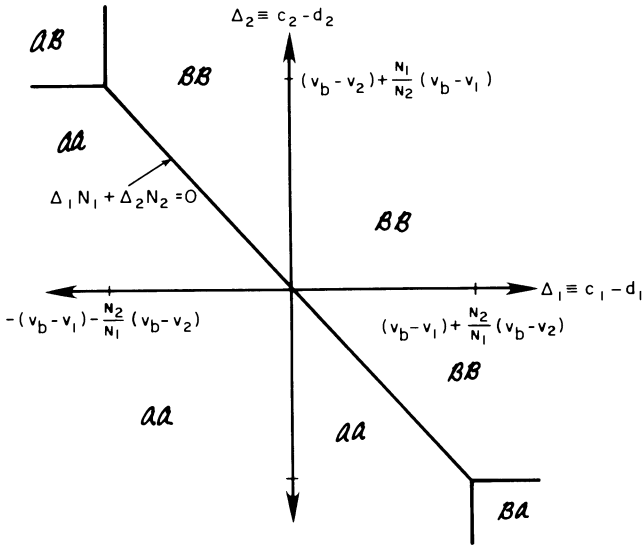

FIG. 2.—Socially optimal technology choice

bodying each technology. Thus each technology is offered at its marginal cost during each period: $p_t = c_t$ and $q_t = d_t$ for $t = 1, 2$.

Taking $\delta_t \equiv \Delta_t$, figure 1 shows that, if one technology is lower cost in both periods, then, as is socially optimal, all consumers purchase that technology. The question of technology choice is richer when the consumers disagree about which technology is the more desirable one. Given the network externalities, each consumer wants all other consumers to purchase his favored technology.

Because each consumer group ignores the negative effects on the other when choosing not to standardize, the private outcome may induce "stranding" or nonstandardization when standardization would be optimal. Figure 3 compares the market outcome and the socially optimal outcome. The diagonally shaded region in the figure represents cases in which there is excessive nonstandardization. Second-period consumers ignore any adverse effects that their technology choice may have on first-period consumers. Similarly, first-period consumers ignore the adverse effects that nonmatching has on later consumers and may choose a technology despite knowing that it will induce stranding.

When standardization does occur, the socially optimal technology may not be selected; there are biases in the market's choice of a standard. The technology that is cheaper in period 1 has a first-mover advantage. When $|\Delta_t| < v_b - v_t$ for both periods, either group of

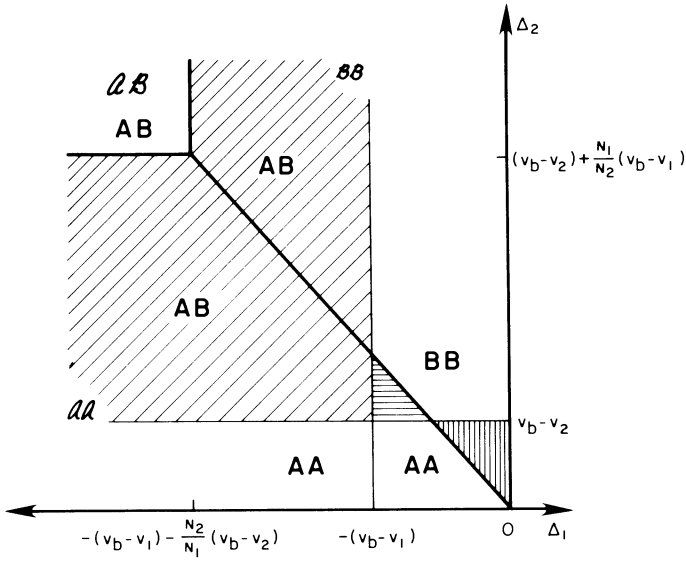

FIG. 3.—Equilibrium vs. optimum: no sponsors. The script characters denote the socially optimal outcomes, with the regions divided by the thick lines. The block characters and thin lines refer to market equilibrium outcomes. The same convention applies to figs. 5 and 7.

consumers would match the other. First-period consumers choose first and lock in their preferred technology, even when it is socially optimal to standardize on the other technology. The range of costs over which this misallocation occurs is given by the vertically shaded area in figure 3. This analysis shows the often-noted tendency to standardize on the technology that initially is superior even though it is the "wrong" technology. Our model shows that this outcome need not be the result of irrationality or impatience.

There is a second bias in the choice of standard. The preferred technology of the larger consumer group can prevail even when it is socially optimal for the preferred technology of the smaller group to do so. The larger group can more easily go it alone. Thus there are cases in which the smaller group, knowing that the larger group will go its own way, caves in and adopts its own less preferred technology. In this way, even the second-period consumers can act as leaders if they are more numerous. In the horizontally shaded region of figure 3 (which is drawn for $N_2 > N_1$), period 2 consumers' preferred technology, B, is adopted as the standard, although total benefits would be larger if A were the standard.

Note that in this subsection, and throughout our analysis, we are assuming that intergenerational transfers are not feasible and hence

that consumers cannot internalize the network externalities over time.[12] This assumption corresponds to the fact that such payments are often impossible because of a free-riding problem in raising the funds for such transfers.

B. *One Sponsored Technology*

An alternative way to internalize the consumption externalities is through the pricing policies of the suppliers. Sponsorship is necessary if prices are to differ from marginal costs. Suppose that only one of the technologies (say B) is sponsored. This pattern of sponsorship would occur if an emerging technology, B, could be patented while the older technology, A, is no longer subject to effective patent protection. In this case, the firm owning technology B (labeled firm B) can set a price above or below marginal cost. Unsponsored technology A is competitively supplied at prices $p_t = c_t$ for $t = 1, 2$. All agents, including firm B, know the marginal costs in both periods and that technology A will be priced at marginal cost.

As usual, we begin the analysis with the second period. The technology adopted by first-period consumers has an installed-base advantage of $v_b - v_2$. Technology B has a (possibly negative) cost advantage of Δ_2. The technology with the net advantage will prevail in the second period. If first-period consumers adopted technology A, then B will win in the second period if and only if $\Delta_2 > v_b - v_2$. If B won in the initial period, then it will also win in the second period if and only if $\Delta_2 \geq v_2 - v_b$.

Now consider the first period. First-period consumers must project second-period sales in making their technology choice. There are several cases to consider. First, suppose that technology B is sufficiently superior that it will be chosen by second-period consumers even if all first-period consumers adopt technology A (i.e., $\Delta_2 > v_b - v_2$). In making their purchases, first-period consumers compare $v_1 - c_1$ with $v_b - q_1$. By setting $q_1 = v_b - v_1 + c_1$, firm B can win both periods' sales and earn total profits of

$$N_1(v_b - v_1 + \Delta_1) + N_2(v_b - v_2 + \Delta_2), \tag{9}$$

where the second-period price is $v_b - v_2 + c_2$. If, instead, firm B loses the first-period competition, it earns total profits (from second-period sales) of

$$N_2(v_2 - v_b + \Delta_2). \tag{10}$$

[12] This assumption is consistent with our earlier assumption that consumers purchasing at a given date coordinate on their Pareto-preferred equilibrium. Unlike intertemporal coordination, within-period coordination requires no transfers since all consumers purchasing at a given date have identical interests.

Comparing expressions (9) and (10), we find that when $\Delta_2 > v_b - v_2$, technology B wins the first-period (as well as second-period) sales if and only if

$$N_1(v_b - v_1 + \Delta_1) + 2N_2(v_b - v_2) \geq 0. \tag{11}$$

When firm B wins in the first period, its price is $q_1 = v_b - v_1 + c_1$. This price may be below its marginal cost, d_1. Firm B is willing to make below-cost sales to first-period consumers because their presence on its network raises the value of technology B to second-period consumers. The sponsor can internalize the external benefits generated when first-period consumers choose the sponsor's technology.

Unlike the first-period price, the second-period price *cannot* fall below marginal cost. Firm B cannot credibly promise first-period consumers that it will subsidize sales in the second period. Thus, in the absence of the ability to commit itself to future subsidies, the sponsor may be unable to internalize the external benefits accruing to first-period consumers.

We turn now to a second case, in which firm B wins the second-period sales if and only if it wins the first-period sales (i.e., $v_2 - v_b \leq \Delta_2 \leq v_b - v_2$). If firm B sets the maximal prices that allow it to win in both periods, its profits are

$$N_1\Delta_1 + N_2(v_b - v_2 + \Delta_2). \tag{12}$$

As long as these profits are positive, selling in both periods is superior to dropping out. Hence, in equilibrium all consumers will purchase technology B if and only if the expression in (12) is positive. Surprisingly, this expression may be positive even when technology B is more costly in *both* periods (i.e., $\Delta_1 < 0$ and $\Delta_2 < 0$). The reason is that firm B is willing to make investments in its technology in the form of penetration pricing in order to build up a customer base, while firms selling the unsponsored technology A are unwilling to do so. Given that firm B has a base of first-period customers, it has an advantage over technology A in the second period, and firm B can earn a return on its investment by making second-period sales at a price above its marginal cost.

The market outcome is illustrated in figure 4.[13] Since only one technology is sponsored, the figure is not symmetric. Because of its ability to invest in a customer base, the sponsored technology B is more likely to be adopted.

[13] The figure uses the fact that, when technology A wins the second-period sales no matter what choice first-period consumers make (i.e., when $\Delta_2 < v_2 - v_b$), first-period consumers compare $v_b - c_1$ with $v_1 - q_1$. In this case, technology B will have positive first-period sales if and only if $\Delta_1 > v_b - v_1$.

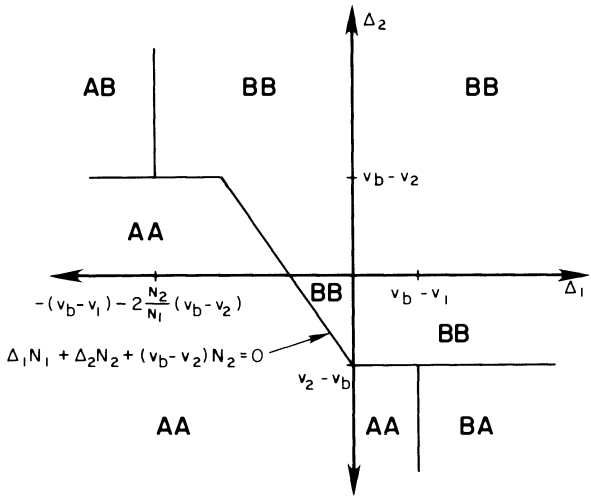

FIG. 4.—Adoption with a single sponsor (B)

The market and the welfare-optimal outcomes are compared in figure 5. With a single sponsor, the market equilibrium still may entail excessive nonstandardization, as is illustrated in the vertically shaded region of the figure; the sponsor ignores period 1 consumers when it wins in period 2. The sponsor internalizes only some of the externalities among consumers. The market outcome also may entail standardization on the sponsored technology in markets where nonstandardization is optimal. This occurs in the cross-hatched area in figure 5.[14]

More generally, there is a bias toward the sponsored technology. In the diagonally shaded region of figure 5, the sponsored technology is adopted although the social optimum entails adoption of the other technology. The most striking case of bias is the one in which technology B wins in both periods even though it has higher costs in each one. The bias is a manifestation of the fact that the sponsor overpromotes its technology. The reason is the "weakened-rival effect": by winning in period 1, firm B faces a rival that is less attractive to consumers in period 2, and thus firm B can appropriate more of the second-period consumer surplus. This transfer is a private, but not a social, benefit of B's winning in the first period.

[14] When the sponsored technology cannot win in the second period ($\Delta_2 \leq v_2 - v_b$), the market may again involve excessive stranding (see the horizontally shaded portion of fig. 5). It is also possible that the *un*sponsored technology is selected as the standard when the sponsored technology would generate higher benefits (the shaded area in fig. 5). Both of these market biases would be corrected if the sponsor were able to commit to second-period subsidies.

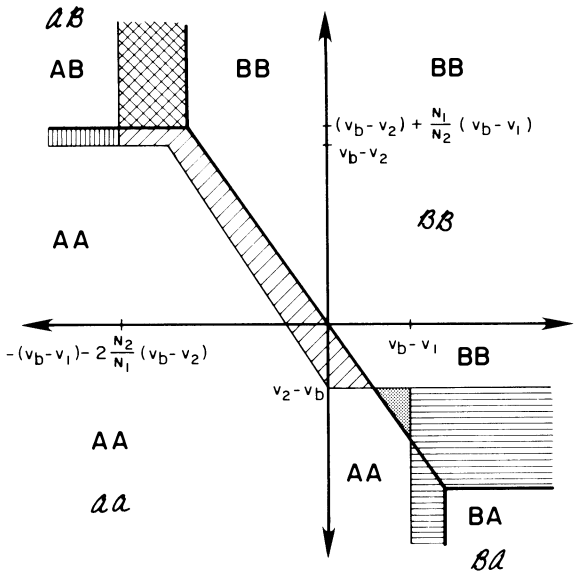

FIG. 5.—Equilibrium vs. optimum with a single sponsor (B)

C. *Both Technologies Sponsored*

When the technologies competing for adoption are both new, each one is likely to enjoy patent protection and hence be sponsored. In this case, the problem is once again symmetric. Hence, we can assume without loss of generality that $\Delta_2 \geq 0$, so that technology B is the cheaper one in period 2.

Consider competition in the second period given first-period sales. The firms play Nash in second-period prices, so either firm is willing to go down as far as its marginal costs in order to undercut its rival. The technology that can offer second-period consumers the greater level of surplus wins all second-period sales and is priced so that it marginally beats the losing one.

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 purchase A (i.e., $\Delta_2 > v_b - v_2$). Consider first-period competition in this case. If technology A wins the first-period sales, then in the second period the maximal price that B can charge satisfies $v_b - c_2 = v_2 - q_2$, or $q_2 = v_2 - v_b + c_2$. Firm B will earn total profits of $N_2[\Delta_2 - (v_b - v_2)]$. 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 $v_1 - p_1$ and $v_b - q_1$. 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 $q_1 = v_b - v_1 + c_1$ in order to win first-period sales. In this event, firm B earns profits of $N_1(\Delta_1 + v_b - v_1)$ 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 if it had lost in the first period (the weakened-rival effect). Its maximal second-period price is given by $q_2 = v_b - v_2 + c_2$. Hence, firm B's second-period profits are $N_2(\Delta_2 + v_b - v_2)$. Comparing total profits under each of the two first-period strategies, we see that it will be profitable for firm B to win first-period sales if and only if

$$(v_b - v_1) + \left(\frac{2N_2}{N_1}\right)(v_b - v_2) > -\Delta_1. \tag{13}$$

Now 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., $\Delta_2 \leq v_b - v_2$). In this case, whichever firm captures the first-period sales will make the second-period sales as well. Conditional on winning the first-period sales, second-period profits are $N_2[(v_b - v_2) - \Delta_2]$ for firm A and $N_2[(v_b - v_2) + \Delta_2]$ 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 firm A wins the first-period sales at price p_1, its profits are

$$N_1(p_1 - c_1) + N_2(v_b - v_2 - \Delta_2). \tag{14}$$

Solving (14) for the price that yields zero profits, we obtain

$$\hat{p}_1 = c_1 - \left(\frac{N_2}{N_1}\right)(v_b - v_2 - \Delta_2). \tag{15}$$

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

$$\hat{q}_1 = d_1 - \left(\frac{N_2}{N_1}\right)(v_b - v_2 + \Delta_2). \tag{16}$$

The firm that has the lower minimal price is the one that will serve all consumers in both periods. Comparing equations (15) and (16), we see that firm B will win if and only if

$$N_1\Delta_1 + 2N_2\Delta_2 > 0. \tag{17}$$

The equilibrium market outcome is illustrated in figure 6. Recalling that the social decision rule calls for standardization on B instead of A when $N_1\Delta_1 + N_2\Delta_2 > 0$, we see that there is a "second-mover advantage" among firms. Suppose that $N_1 = N_2$, that firm A has the cheaper technology in period 1, and that firm B has the cheaper technology in period 2, with $0 < -\Delta_1 = \Delta_2$. As long as the cost

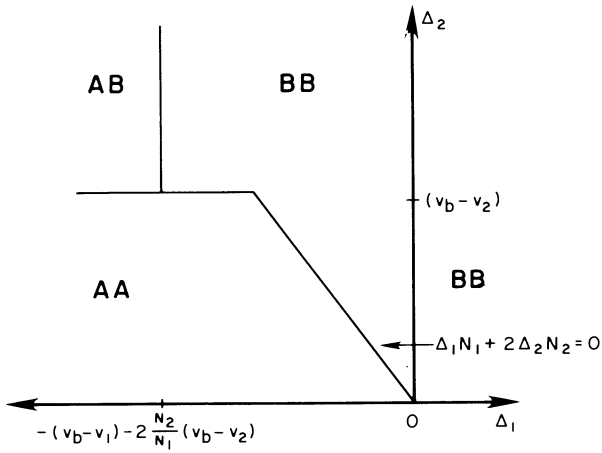

FIG. 6.—Equilibrium adoption with two sponsors

differences are not too large, the market equilibrium entails all consumers' purchasing technology B. The reason is that firm A cannot credibly promise to price below cost in the second period, but firm B *can* price below cost in the first period. Of course, at some point the cost differences become so large that they dwarf the network effects, and consumers in each period choose the technology that is cheaper at the time.

Figure 7 compares the market equilibrium and the second-best outcomes. In the horizontally shaded region of the figure, consumers split their technology choices across periods even though matching would be socially optimal. This excessive splitting occurs only in cases in which the socially optimal pattern of technology choice is AA but the private equilibrium is AB. Because of the timing of play, firm A is unable to internalize the stranding externality that second-period consumers impose on first-period consumers.

With two sponsors, the wrong technology may be chosen when standardization does occur. In the light of the second-mover advantage, we find that the market equilibrium is biased toward adoption of the technology that is cheaper in the second period. The vertically shaded area in figure 7 represents markets in which the socially optimal pattern of technology choice is AA but the market outcome entails BB. Firm B is able to win in the first period despite its higher first-period costs because consumers expect firm A to drop out of the market in period 2, even if it wins in the first period. In the first period, firm A cannot credibly promise to make second-period sales. Firm B's incentives to win in the first period are further strengthened by the weakened-rival effect. Hence, there is excessive choice of technology B in the first period.

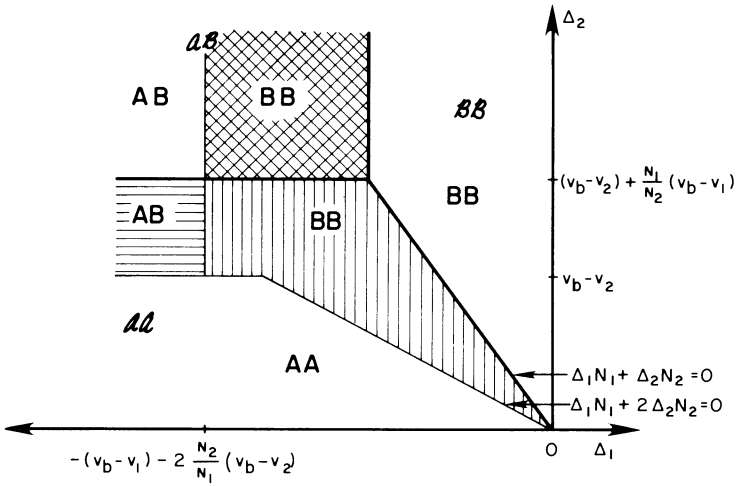

FIG. 7.—Equilibrium vs. optimum with two sponsors

This tendency to standardize on the emerging technology is the opposite of the story one typically hears about industry evolution. With typewriter keyboards, for example, the technology that was "cheaper" in the first period won, to the detriment of later consumers.[15] The typewriter example conforms to our first-mover advantage in the absence of sponsors; there was no sponsor for any given keyboard. Our analysis here suggests that rather different dynamics may arise in the presence of well-defined property rights.

V. The Durable Goods Monopolist on His Head

Suppose now that demands in the second period are elastic, and consider the case of a single sponsor, say firm B. If firm B has market power in the second period, first-period consumers rationally will expect B to exercise this market power, giving rise to a smaller expected network than if marginal cost pricing were practiced in the second period.[16] One can show by example that, in the first period, the sponsored technology may be at a disadvantage relative to the unsponsored one because the latter can credibly commit to marginal cost pricing. This effect is simply a variant of the time consistency

[15] "Cost" refers here to the hedonic cost, where adjustment is made for ease of use. The first period corresponds to early mechanical machines that were subject to jamming. The second period corresponds to modern, nonjamming equipment operated by touch-typists. For the latter, the Dvorak keyboard is superior to QWERTY.

[16] This point is one example of the fact that sponsorship creates market power, which leads to a resource misallocation when demands are elastic.

problem that gave rise to a second-mover advantage in the case of two sponsored technologies that we analyzed above.

The sponsor's problem is the opposite of the durable good monopolist's problem, as posed by Coase (1972) and studied further by Bulow (1982). A durable good monopolist cannot commit itself to restricting future production and maintaining its price over time. Consumers anticipate the falling prices and thus are willing to pay less for early units since their asset value is lower. In our model, the link between prices in different periods comes through the positive consumption externalities. Here, early consumers benefit from lower prices and larger sales in later periods. Thus the time consistency problem for the sponsor is that it cannot commit to a second-period price other than the "high" one that will maximize profits at the time.

There may be mechanisms by which a sponsor can commit himself to setting low second-period prices. For example, the sponsor could make research and development expenditures or physical capital investments that lower its marginal costs. Alternatively, the firm might make its product design public, or the sponsor might advertise in advance that low prices will be offered in the second period to some or all consumers. Given rational first-period consumers, it will be in the firm's interest to limit its own ability to exercise second-period market power.

This point leads to a warning for antitrust enforcement. An industry observer could mistake investments that commit the firm to lower prices for entry deterrence or predation. Similarly, below-cost pricing in the first period need not be indicative of predatory behavior. Finally, our analysis shows that a cartel of producers may be socially desirable to the extent that it allows them to set later prices above marginal cost and thus generates incentives to invest in a new technology in the presence of network externalities. Pricing at the marginal cost of production in each period may not be socially optimal.

VI. Extensions

There are several directions in which to extend our analysis. One could allow for within-period consumer heterogeneity. Within-period heterogeneity differs from our between-period heterogeneity in terms of the timing of purchase decisions; there is no first or second mover within a single period. Within-period heterogeneity gives rise to benefits from variety and to the possibility of multiple equilibria, but the basic forces pushing toward de facto standardization clearly would remain.

Another extension is to consider the case of ex ante uncertainty about the relative attractiveness of competing technologies. There

may be uncertainty about second-period costs or about the preferences of consumers over the rival technologies.[17] A consumer purchasing the technology early is unlikely to be certain of future costs or of the adoption decisions by consumers who will make purchases later. This uncertainty may have the greatest effect if consumers can choose when to purchase the technology. With intertemporal substitution, some consumers may choose to wait for cost and demand uncertainty to be resolved before they commit themselves to a specific technology.

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[17] In Katz and Shapiro (1986) we examine compatibility choice in a model with uncertainty about the second-period production costs of the two technologies.