An Open System and Its Effects on R&D

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In open systems firms give up their property rights to technologies and permit other companies to use these technologies. We ask whether an incumbent can establish its socially inefficient technology as a market standard by choosing an open system, thus preempting an entrant from developing a more efficient technology. We study how the incumbent's architecture choice affects an R&D game between the entrant and the incumbent by changing consumers' expectations of a future market standard. It is shown that an incumbent has an incentive to preempt an entrant' competing technology by choosing an open system, but that the open system might result in a premature market standard.

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Keep your friends close, but your enemies closer.

> - *The Godfather, Part II*

1   Introduction

Companies usually try to protect their technologies from rival companies' imitation and cloning. However, in markets with network effects,[1] the owners of proprietary technologies sometimes adopt an *open system.*[2] That is, they allow others to use their technologies. For instance, while key components and software of traditional mainframe computers were produced in-house, IBM decided to open its PC architecture. IBM's open architecture made entry into the IBM PC clone market very easy, as anyone could buy the same components and combine them. Intel's early licensing policy and Ethernet technology are both good examples of open systems. Recently, Nokia announced that it would share its mobile technology with other firms.

Even though open systems receive a great deal of attention, little research has been done on how open systems affect a future technology path or, equivalently, R&D competition among firms. This article explores how an incumbent's system choice affects an entrant's R&D activity. We ask whether an incumbent can preempt a rival technology by choosing an open system. More specifically, can an incumbent, by adopting an open system, make its socially inefficient technology the market standard while an entrant is developing a more efficient technology?

To answer these questions, we develop a simple formal model that illustrates the relationships among an incumbent's architecture choice, consumers' technology choices, and an entrant's R&D decision. Using this framework, we analyze the welfare effect of the open system. Under the open system, the incumbent's technology becomes 'open', and the entrant has one more technology choice. Is social welfare always (weakly) higher under the open system than under the closed system?

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[1] Network effects occur when the benefits from consuming a product increase with the size of its consumer group. For example, the value of the IBM-compatible PC increases when more consumers use it as more varieties of software are expected to be supplied at lower prices.

[2] The Unix X/Open consortium defines open systems as systems and software environments based on standards that are vendor-independent and commonly available.

Our answers to these questions depend on the potential rivalry in R&D competition. Surprisingly, we show that in situations characterized by network effects, open systems can reduce social welfare, as compared with closed systems.

In an industry characterized by network effects, the value of a product depends on the size of its network. A firm that owns a specific technology has a strong incentive to increase consumers' confidence in the technology by setting it as the market standard. In an influential paper, Katz and Shapiro (1986) study the case in which two firms compete, each attempting to set its own technology as the market standard. They focus primarily on how firms use penetration pricing as a strategic tool. However, a fundamental decision by a firm is whether it adopts a closed or an open system: A firm can choose a closed system and adopt what Katz and Shapiro (1986) call 'penetration pricing'. Also, a firm can adopt an open system and allows other firms to use the technology.

Our article allows an incumbent to choose either an open or a closed system and studies how these system choices affect market outcomes.[3] In period one, an incumbent makes its architecture choice (either an open or a closed system) and then sells its durable goods that exhibit network effects. An entrant undertakes an R&D project between periods one and two and enters the market in period two. Depending on the incumbent's system choice, the entrant has different R&D choices. Under the closed system, the entrant can attempt to develop a new, superior system, which is incompatible with the incumbent's. However, under the open system, the entrant has an additional option of adopting the incumbent's technology and improving upon it. We can think of the first one as product R&D, and the second one as process R&D.

We will solve these two subgames in which the incumbent chooses the closed and the open systems, respectively. Then, we will study how the incumbent's architecture choice affects consumers' expectations of a future

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[3]Besides penetration pricing and the open-system strategies, there are several other strategies that the incumbent can use. The incumbent may use a contingent pricing scheme, such as a refund, saying: "If the size of installed base does not reach a specific level in the next year, we will refund some of your money." In this way, the firm may convince consumers that its product will have a high-value network. However, it is hard to credibly commit to these policies. First, it is hard to verify the size of the installed base since the firm can, to a certain degree, manipulate the data on that. Second, the firm may even go out of business in the future.

market standard, and how the consumers' expectations influence the entrant's R&D choice.

Under the closed system, the incumbent can adopt the 'penetration pricing' strategy. That is, the incumbent may supply its products below production cost to build a large installed base; in period two, the firm can recoup this loss by charging a price above cost with the advantage of the installed base. However, under the closed system, the entrant has only one choice, product R&D. There is a standard war between the incumbent's and the entrant's technologies. Depending on the R&D result, there is a chance that the entrant's product will be the second-period market standard. That is, there is uncertainty about which technology will be dominant in period two. First-period consumers can wait until period two and buy a product from a winner in the standard war. In order to sell its products in period one, the incumbent has to compensate for the uncertainty by lowering its price. The penetration price may have a negative profit margin, and the strategy can be very costly because the firm may have to sustain considerable losses while building the installed base.

As an alternative, the incumbent may adopt an open system and permit the entrant to use its technology. Under the open system, the entrant can choose between process R&D and product R&D. The advantage of undertaking process R&D is that the entrant can make its product compatible with the incumbent's. The optimal R&D choice for the entrant depends on the size of the incumbent's installed base. Thus, first-generation consumers' purchase history has an influence on the entrant's optimal R&D choice. When a large number of consumers have already bought the incumbent's product, it becomes optimal for the entrant to adopt and improve the incumbent's technology. That is, the open system strategy assures consumers (in equilibrium) that the incumbent's technology will be adopted by the entrant, provided that a large number of consumers have already chosen the incumbent' technology. Thus, open systems increase consumers' willingness to pay in period one. However, this course has its own disadvantage: the incumbent will lose the rent derived from the monopoly of the technology when the entrant succeeds in improving quality/cost.[4] This paper shows that the

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[4]For instance, in the early stage of the IBM compatible PC market, IBM made considerable profits, and its PC revenues were almost as large as mainframe equipment revenues. However, IBM's market share shrank from 30% in 1984 to 16% in 1991, while other clone companies such as Dell and Gateway increased their market shares with successful process

incumbent may optimally choose the open system knowing that it will lose all second-period market sales.[5] Also, the incumbent is more likely to choose the open system as the probability of the entrant's succeeding in product R&D grows. In other words, the incumbent wants to preempt the entrant's competing technology.

This paper also examines welfare implications of open versus closed systems. The open system has several advantages in terms of social welfare. When the incumbent chooses the closed system, there is confusion over the second-generation standard, and the process of adopting a market standard becomes slow. In addition, consumers who choose the 'wrong' technology will be left out of the network effect. The open system allows the market standard to be reached more quickly and thereby maximizes network effects.

Despite the above-mentioned benefits of an open system, this paper shows that the social welfare level can be lower under the open system than under the closed system. The entrant's optimal R&D choice under the open system depends on how many consumers have already bought the incumbent's product. When a large number of consumers have already bought the incumbent's product, the entrant will adopt the incumbent's technology. Suppose that it is socially optimal for the entrant to develop its own system and for all consumers to buy the entrant's product. Do first-generation consumers wait until period two? Not necessarily. Even though they pay an opportunity cost of waiting, they must pay an equilibrium price in period two. The second-period price is not necessarily low enough to reward consumers for waiting. That is, by choosing an open system, the incumbent can sell its product to first-period consumers and, thus, force the entrant to adopt the incumbent's technology rather than to develope its own system. That is, the incumbent can set its technology as the market standard, and we may have a premature market standard under the open system.

There are several papers in the literature on network effects.[6] Katz and Shapiro (1986) analyze a case in which both of two firms use the penetration pricing strategy in a two-period model. Our paper, however, considers

innovations.

[5] Although observers often suggest that IBM made a mistake by choosing an open system, Grindley (1995) correctly points out that these criticisms overlook the considerable profits IBM made in the early stages of the PC industry.

[6] For a more comprehensive survey, see Katz and Shapiro (1994) and Benson and Farrell (1994). See, Choi (1994, 1996) Economides (1989), Farrell and Saloner (1986), Katz and Shapiro (1986), among others.

the case in which the incumbent can choose either the penetration-pricing strategy or the open-system strategy. We analyze how the open system strategy changes the market competition and evaluate the welfare effects of open systems.

Gallini (1984) and Farrell and Gallini (1988) show that a monopolist can optimally share its technology with other firms.[7] Note that, in their papers, the availability of the incumbent's technology determines the entrant's technology. However, in our paper, the first-generation consumers' consumption decisions determine the entrant's R&D choice. Specifically, in our model, the incumbent's system choice itself can influence the entrant's R&D decision only if a large number of first-generation consumers buy the incumbent's product. Also, their papers show that the incumbent's decision to share technology with others improves both the incumbent's profitability and social welfare, whereas our paper shows that the open system strategy can reduce social welfare.

Lerner and Tirole (2000) focus on different aspects of open source software. The main focus of Lerner and Tirole (2000) is that the literature on career concerns can adequately explain several (stylized) facts of open source software.

In addition, several papers on piracy and copyright (Liebowitz, 1985; Conner and Rumelt, 1991; Shy and Thisse, 1999) show that a producer may deliberately choose a low degree of copy protection for its product.[8] None of these studies, however, considers how an incumbent's system choice affects an R&D game between an incumbent and an entrant through consumers' choices.

The rest of the paper is organized as follows. Section 2 describes the model and the timing of moves and imposes several parameter restrictions. Sections 3 and 4 analyze the market outcome under the closed system and under the open system, respectively. Section 5 studies the welfare implications of

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[7]Gallini (1984) analyzes the ex ante incentives of licensing and points out that the incumbent can eliminate inefficient R&D expenditure by making a licensing contract with a rival. Farrell and Gallini (1988) show that a monopolist can optimally invite other firms in order to guarantee that complementary products will be supplied at a low price.

[8]In Conner and Rumelt (1991) and Shy and Thisse (1999), there are two types of consumers, support-oriented and support-independent consumers. In their models, a firm uses low copy protection as a tool of market segmentation between the two different types of consumers. However, in our paper, since all consumers are homogeneous, firms do not have those incentives.

the open system. Section 6 compares (pure) open systems with licensing contracts. Concluding remarks follow.

2   Model

This paper builds a two-period model of durable-goods pricing and network externalities. A continuum of identical consumers arrives in each period. The size of each group is denoted by n_t, $t = 1, 2$. First-generation consumers can either buy a product or wait until period two. In period two, active consumers consist of first-generation consumers who have not purchased in period one and second-generation consumers who have just arrived at the market. They decide whether to buy a product and, if so, which product to buy. All players (consumers and firms) have a common time discount factor $\delta = 1$. If a first-generation consumer switches to product j in period two after having used product i in period one, she must pay a switching cost, S. We assume that the switching cost is large enough that consumers with good i will not switch to good j in period two.

The amount of utility a consumer gets from a product i in each period is, $a + bI_i(t)$: the basic utility a, and the benefits from the networking externalities, $bI_i(t)$, where b is a coefficient of externalities, and $I_i(t)$ is the size of the installed base of product i in period t. Thus, the benefits from a product increase with the size of its consumer group.[9] Since it is a durable good, the net benefits of buying product i in period one is $a + bI_i(1) + a + bI_i(2) - p$, where p is the price of the product in period one. Since the value of buying product i in period one depends on $I_i(2)$, consumers need to estimate the size of $I_i(2)$ in making their purchasing decisions in period one.

There are interesting dynamics between $I_i(1)$ and $I_i(2)$. The current network size influences the future size, since the product with a large current installed base will be more attractive to future consumers. The expected future network size, in turn, has an impact on the size of the current network.

There is an incumbent producer of a durable good. The incumbent chooses either an open system or a closed system and sells its product in

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[9]In a hardware/software market, as more consumers choose the same hardware technology, more software programs for the technology can be supplied at lower prices. We can consider this model as a reduced form of a model where complementary products are being developed, which in turn increases the value of the base product. See Church and Gandal (1992) and Chou and Shy (1990) for indirect network effects.

period one. Its unit production cost is c. A potential entrant undertakes R&D between periods one and two and enters the market in period two.[10] The entrant's production cost depends on the R&D result.

There are two kinds of R&D projects that the entrant can undertake: to develop its own system, or to adopt and improve upon the incumbent's system. We can think of the first one as product R&D, and the second one as process R&D.

Under the closed system in which the incumbent denies its technology to the entrant, the entrant has no choice but to conduct product R&D. Under the open system, the entrant has one more R&D choice, process R&D. When the entrant undertakes process R&D, its product is compatible with the incumbent's.[11] The entrant can make its products compatible with the incumbent's product only if the incumbent opens its system.[12]

When the entrant undertakes product R&D, the unit production cost is c_L with probability π and c with probability $1 - \pi$, where $c_L < c$. When the entrant undertakes process R&D, the unit production cost becomes c_H with certainty, where $c_H < c$. We assume that $c_H > c_L$, implying that the entrant can achieve the lowest production cost with product R&D. Since all consumers are identical in their valuations of quality, any quality improvement can be represented by a cost reduction, without loss of generality. Lower cost is a "short-cut" to represent a "better" product.[13] Also, product R&D and process R&D can be interpreted as a drastic innovation and minor improvement, or as a revolutionary approach and evolutionary approach.

For simplicity, there is no cost to R&D. We assume that the incumbent does not invest in R&D. Allowing either a positive R&D cost or the incum-

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[10]This paper does not endogenize the entry decision of the entrant. However, this paper is easily extended to the case where there is an entry cost. The main results are robust to this change.

[11]Usually, there are some compatibility losses under the open system. In the case of IBM compatible PC, some graphic cards have compatibility problems with some sound cards, etc. However, as long as the extent of compatibility is substantially large, we still get the same qualitative results.

[12]For example, no one can sell an audio player in the United States that will play CDs without the consent of Philips and Sony. The DVD player can read regular CDs with the consent of Sony and Philips. See Shapiro and Varian (1998).

[13]Suppose that the entrant can develop a new product with product R&D, and the size of the quality improvement over the incumbent's product is Δq. As long as $\Delta q = c - c_L$, the analysis remains the same.

bent's R&D activities would complicate the exposition without changing the qualitative result. The main results of this paper are robust to these changes. We will discuss the robustness at the end of this paper.

Both firms and consumers know everything that has happened in previous moves. The equilibrium concept is SPNE.

Parameter Restrictions

Assumption 1: $a + bn_2 \geq c$
Assumption 2: $bn_1 < c - c_L$

(A1) is sufficient for all consumers to buy a product in equilibrium.

The incumbent can build an installed base in period one, and under the closed system the installed base gives the incumbent an advantage in the second-period market competition. (A2) implies that even if the incumbent builds the largest installed base in period one, the entrant can overcome it with successful product R&D. Therefore, the second-period market standard under the closed system will be decided after the entrant's R&D result is revealed.

Equilibrium Selection
Because of network effects, we can have multiple equilibria: a given set of prices will not result in an unique set of purchase decisions by consumers. This paper will use the same equilibrium selection as the one adopted in several papers in the literature (see Katz and Shapiro (1986), Choi (1994) and Carlton and Waldman (1998), among others). If a Pareto dominant equilibrium exists for consumers buying in the same period in a subgame that starts with the consumers' choices, the Pareto dominant equilibrium will be realized in the subgame. That is, we assume that when there are multiple equilibria, consumers buying in the same period can coordinate their purchase decisions.

We need to explain this equilibrium selection in more detail. First, consider period two. Second-period decision-making consumers consist of first-generation consumers who have not bought a product and second-generation consumers who have just arrived. Since all consumers are identical, they will agree on which outcome yields higher consumer surplus. If all consumers get a higher utility from one equilibrium than from other equilibria, then the Pareto dominant equilibrium for the consumers is realized in the subgame.

Now, consider the first period. Each first-generation consumer makes her decision having calculated the resulting second-period equilibrium, in which her calculation uses the second-period equilibrium selection discussed above. After the incumbent announces its price, there can be several (refined) continuation SPNEs. The market outcome is the SPNE in which the first-generation consumers get the highest continuation payoff among all (refined) continuation SPNE. Suppose that there are two SPNE. One SPNE is for all first-generation consumers to wait until period two, and the other SPNE is for all first-generation consumers to buy the incumbent's product. If all consumers get a higher utility from one SPNE than from the other, then the Pareto dominant equilibrium for first-generation consumers is realized.

For example, consider a simple one-period model, in which firms 1 and 2 produce identical but non-compatible products. First, they announce their prices, and then consumers choose between products 1 and 2 simultaneously. Because of network externalities, there exists a coordination problem among consumers. However, the equilibrium selection makes this analysis simple. When all consumers choose the lowest-priced product, every consumer gets the highest payoff. Moreover, this outcome is a NE. Therefore, it is a unique equilibrium consistent with the equilibrium selection for every consumer to choose a product with the lower price. Since only the lowest-priced product sells, firms are willing to lower their prices down to their marginal costs. Therefore, the competition between the two firms becomes Bertrand competition.

3 Closed System

In the beginning of the game, the incumbent chooses either a closed or an open system. We will solve both subgames, where the incumbent chooses the closed system in one subgame and the open system in the other, respectively. Then we analyze the optimal system choice for the incumbent and the welfare effect of the open system.

Under the closed system, the entrant has only one R&D choice: product R&D. The entrant enters the second-period market with its own system and competes with the incumbent.

3.1   The Second Period

We begin our analysis by considering the purchasing decisions of current consumers in period two.[14] The consumers know the size of the installed base that was established in period one.

The incumbent and the entrant announce their prices p_2 and r_2. If all current consumers buy the incumbent product, they each get $a + b(n_1 + n_2) - p_2$. If all of them buy the entrant's product, they each get $a + b(n_1 + n_2 - I_I(1)) - r_2$. So, if $p_2 - bI_I(1)$ is lower (higher) than r_2, they get the highest payoff from buying the incumbent's product (the entrant's product). Moreover, it is NE. Therefore, the unique equilibrium consistent with the equilibrium selection is that all current consumers choose the incumbent's product (the entrant's product) if and only if $p_2 - bI_I(1)$ is less (higher) than r_2.

Since only the lowest-priced product sells, firms are willing to lower their prices as far as the marginal costs. The entrant can sell its product only if its unit production cost is lower than $c - bI_I(1)$. When product R&D is successful, the entrant can produce its product with unit production cost c_L, which is lower than $c - bI_I(1)$ by (A2). Thus, only the entrant sells its product at price $c - bI_I(1)$ in period two. However, when product R&D fails, both firms have the same unit production cost. However, because of its installed base, only the incumbent sells its product at price $bI_I(1) + c$.

(A2) ensures that, even if the incumbent builds the largest installed base in period one, the entrant can overcome it with successful product R&D. Thus, the second-period market outcome depends on the R&D result.

Lemma 1: *All current consumers buy products from only one firm in period two. When product R&D fails, all current consumers buy the incumbent's product at $c + bI_I(1)$. When product R&D succeeds, all current consumers buy the entrant's product at $c - bI_I(1)$.*
Proof. Appendix ∎

While the incumbent has the advantage from the installed base, the entrant can have the cost advantage, depending on the R&D result. The relative size of these two effects determines the second-period competition. When the entrant fails in R&D, the incumbent's profit margin in period two is $bI_I(1)$

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[14]The current consumers consist of the first-generation consumers who did not purchase in period one and the second-generation consumers who have just arrived at the market.

and increases with $I_1(1)$. Thus, the incumbent has an incentive to build its installed base in period one.

3.2   The first period

As the analysis of the second-period subgame shows, there is an uncertainty about the second-period market standard. This uncertainty has an influence on the first-generation consumers' choices and the incumbent's profitability.

Penetrating Prices

Each first-generation consumer makes her decision taking the purchase decisions of other first-generation consumers as given and having calculated the resulting second-period equilibrium. First-generation consumers have two choices, buying the incumbent's product in period one, or waiting until period two to buy a product. By buying the incumbent's product in period one, consumers can enjoy a positive period-one flow utility. However, if the entrant succeeds in product R&D, they will miss the beneficial interactions with consumers with the entrant's product in period two. Suppose that all first-generation consumers buy the incumbent's product, and all second-generation consumers buy the entrant's product. The missed interaction with consumers with the entrant's product is measured by bn_2 for each first-generation consumer. Instead, by waiting until period two, consumers can find out which firm will be the winner of the second-period competition and buy a product from the winner, which maximizes the beneficial network effects in period two. Thus, in order to sell its products in period one, the incumbent needs to compensate its potential customers for the uncertainty about the second-period standard. p_1 will denote the price of the incumbent's product in period one under the closed system. Lemma 2 shows how the uncertainty suppresses the incumbent's first-period price.

Lemma 2: *There is a unique SPNE consistent with the equilibrium selection. If p_1 is lower than or equal to $a+bn_1 + c - \pi_2 bn_2$, all first-generation consumers buy the incumbent's product in period one. Otherwise, they wait until period two.*

Proof. Appendix ∎

The highest price at which the incumbent can sell its products in period one is $a+bn_1 + c - \pi_2 bn_2$. As is standard in the pricing of durable goods,

the (equilibrium) first-period price is the sum of the first-period flow utility
and the expected second-period value. The price consists of three parts: the
first-period flow utility, $a + bn_1$; the expected second-period price, c; and
the amount of compensation the incumbent has to make for the uncertainty,
$-\pi bn_2$.[15]

When the incumbent chooses the penetration pricing strategy, its profit
margin (price minus cost) in period one is $a+bn_1 - \pi_2 bn_2$, which can be
negative. However, when the entrant's R&D fails, the second-period profit
margin, bn_1, is positive. Therefore, the incumbent has an incentive to build
its installed base in period one for the second-period profit. This strategy is
analogous to the penetration pricing strategy in Katz and Shapiro (1986). By
selling its products in period one, the incumbent gets the following expected
payoff,

$$\Pi_1^p = (p_1 - c)n_1 + (1 - \pi)(p_2 - c)n_2$$
$$= (a + b(n_1 - \pi n_2))n_1 + (1 - \pi)bn_1 n_2.$$
[Superscript p denotes penetration.]

The delay case

When π is quite high, it becomes costly for the incumbent to compensate
for the uncertainty, and the incumbent may suffer considerable losses. There-
fore, it is not profitable for the incumbent to use the penetration strategy. In
detail, if $\pi > \frac{a+bn_1}{2bn_2} + \frac{1}{2}$, the incumbent's profit from the penetration strategy
becomes negative. Thus, the incumbent is forced to delay selling its product
until the uncertainty is resolved.[16] In this case, the incumbent's expected
payoff is $\Pi_1^d = 0$, where superscript d denotes delay. The necessary condition
for us to have the delay case is $n_1 < n_2$. That is, as the industry develops,
more consumers arrive.[17]

The incumbent's (reduced) profit from the closed system is $\Pi_1^c = Max[\Pi_1^p, \Pi_1^d]$. The incumbent will choose the penetration strategy only when the profit

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[15]The expected second-period price is one element of the first-period market price, since
the first-period consumers can wait and buy a product in period two. When all first-
generation consumers wait, the second-period price will be c.

[16]For example, in the case of AM stereo, radio stations delayed the investment in equip-
ment due to uncertainty over which technology would prevail. See Shapiro and Varian
(1998)

[17]In order to have the delay case, $\frac{a+bn_1}{2bn_2} + \frac{1}{2}$ must be less than 1. The necessary condition
for $\frac{a+bn_1}{2bn_2} + \frac{1}{2} < 1$ is that $n_1 < n_2$.

level from the penetration strategy is positive.

Lemma 3: *The incumbent will choose the penetration strategy only if* $\pi \leq \frac{a+bn_1}{2bn_2} + \frac{1}{2}$.

4   Open System

This section analyzes how the open system affects consumers' expectations of the second-period market standard and how network consideration affects the entrant's choice between product R&D and process R&D.

4.1   The Second Period

In the open system, the entrant can choose between two R&D projects: product R&D and process R&D. There is a trade-off between the two. With process R&D, the entrant can make products compatible with the incumbent's, but with product R&D, it can achieve the lowest cost.

When the entrant undertakes process R&D, products are compatible with each other, and the second-period market competition becomes just Bertrand competition. The entrant can beat the incumbent with $r_2 = c - \varepsilon$, and the entrant's profit becomes $(c - c_H)(n_1 + n_2 - I_I(1))$.

When the entrant chooses product R&D, however, it can develop a new, superior system, but needs to compensate its potential customers for the missed network interactions with the incumbent's product. The outcome is the same as that of the previous closed system subgame (section 3.1). The entrant can make profits only when product R&D is successful. The entrant's expected profit is $\pi(c - bI_I(1) - c_L)(n_1 + n_2 - I_I(1))$.

The size of gains from making its product compatible with the incumbent's depends on the size of the installed base. Thus, the size of the incumbent's installed base determines the entrant's optimal R&D choice.

Lemma 4 *In the open system subgame, the entrant chooses process R&D if and only if* $I_I(1) > \bar{I} = \frac{1}{b\pi}(\pi c - \pi c_L - c + c_H)$.

If $\bar{I}$ is either below zero or above n_1, the entrant's R&D choice does not depend on the first-generation consumers' choices.[18] We are interested in the

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[18]If $\bar{I}$ is below zero, the entrant always chooses process R&D. If $\bar{I}$ is above n_1, the entrant always chooses product R&D.

cases in which consumers' purchase history alters the optimal R&D choice for the entrant. Thus, we will look at the case in which first-generation consumers' choices determine the entrant's optimal R&D choice. (A3) is a sufficient condition for $\bar{I}$ to be between zero and n_1.

Assumption 3: $\pi(c - c_L) > (c - c_H) > \pi(c - bn_1 - c_L)$

(A3) ensures that the entrant will optimally choose process R&D if all of the first-generation consumers have bought the incumbent's product. Also, even when the incumbent chooses the open system, the entrant will not adopt the incumbent technology if all of the first-generation consumers wait.

Please notice that the incumbent's open-system strategy itself does not force the entrant to adopt the incumbent technology. It can have an influence on the entrant's R&D choice only through the first-generation consumers' consumption decisions.

4.2 The first period

What made IBM PC, Ethernet, and VHS market standards was the fact that consumers, retailers and producers expected these technologies would be market standards and, thus, were more willing to jump aboard the bandwagon. In this section, we examine how the open system affects a consumer's expectation of a future market standard.

In the open system, if all of the first-generation consumers buy the incumbent's product, the entrant will choose process R&D. Expecting that the incumbent's technology will be the market standard, consumers do not need to worry about the possibility that the incumbent's product becomes obsolete in terms of network effects in period two. The expectation that the entrant will adopt the incumbent's technology increases consumers' willingness to pay for the incumbent's product. p_1^o will denote the price of the incumbent's product in period one under the open system.

Lemma 5 *There is a unique SPNE consistent with the equilibrium selection. If p_1^o is lower than or equal to $a + bn_1 + c_1$, all first-generation consumers buy the incumbent's product, expecting that their purchase will induce the entrant to adopt the incumbent's technology. Otherwise, they will wait until period two.*

Proof. Appendix ∎

The highest price at which the incumbent can sell its product in period one under the open system is $a + bn_1 + c$. This price consists of the expected second-period equilibrium price, c, and the first-period flow utility.

If we compare this price with the penetration price under the closed system, we find that the price under the open system is higher than the penetration price by πbn_2. This increase comes from the fact that the incumbent does not need to compensate for the uncertainty about the second-period market standard, and the price has a positive profit margin ($p_1^o - c = a + bn_1 > 0$) in period one.

In summary, the open system increases a consumer's expectation that the incumbent's technology will be the market standard. Due to this increased expectation, consumers buy the incumbent's product, which makes it unprofitable for a potential entrant to establish its own incompatible networks. The entrant adopts the incumbent's technology, thus validating consumers' expectations.

The incumbent's system choice

So far, we have solved both subgames where the open and closed systems are chosen, respectively. Each system has its advantages and disadvantages. With the closed system, the incumbent can earn a profit as a monopoly supplier of the technology, and the incumbent's profit becomes $Max[\Pi_1^d, \Pi_1^p]$. With the open system, the incumbent resolves the uncertainty of the market standard and gets high profits before a new firm enters to compete away profits. However, the incumbent will lose the second-period market, and its total profit under the open system is $(a + bn_1)n_1$.

Figure 1 compares profits levels under the open and closed systems. When π is less than $\frac{1}{2}$, the incumbent chooses the penetration strategy under the closed system. When π is higher than $\frac{1}{2}$, the incumbent chooses the open system strategy.

[Figure 1 here]

Under the closed system, the delay case is realized when π is higher than $\frac{a+bn_1}{2bn_2} + \frac{1}{2}$. However, If π is higher than $\frac{1}{2}$, the incumbent optimally chooses the open system, and all first-generation consumers buy the incumbent's product in period one. Therefore, the open system excludes the delay case, which could be realized under the closed system.

Proposition 1 *The optimal system choice for the incumbent depends on the size of π. When $\pi \leq \frac{1}{2}$, the incumbent optimally chooses the penetration strategy under the closed system. When $\pi \geq \frac{1}{2}$, the incumbent optimally chooses the open system. The open system excludes the delay case.*

The incumbent is more likely to adopt the open system as the entrant's probability of succeeding at product R&D increases. The entrant might well prefer to fight between standards rather than within standards. However, the incumbent moves first, thereby forcing the entrant to adopt its technology. That is, the incumbent can preempt the entrant's product R&D by choosing the open system.

5 Welfare Analysis

The open system has several advantages in terms of social welfare. Under the closed system, the technology adoption process may be delayed. In addition, we can have a case in which some consumers have the incumbent's product, and some consumers have the entrant's product in period two. The open system allows the market standard to be reached more quickly and maximizes network effects. Also, under the open system, the incumbent's technology becomes 'open', and the entrant has one more R&D option. However, there is an opportunity cost of not undertaking product R&D. This section will study the social welfare effect of the open system.

Let us compare the following three paths. One path (penetration path) is that all first-generation consumers buy the incumbent's product, and the entrant undertakes product R&D. Another path (delay path) is that all first-generation consumers wait until period two, and the entrant undertakes product R&D. The third path (open system path) is that all first-generation consumers buy the incumbent's product, and the entrant undertakes process R&D. Social welfare under the respective paths are described in the following equations.

$$
\begin{aligned}
SW^p &= n_1(2a + 2bn_1 + (1-\pi)bn_2 - c) + n_2(a + bn_2 + (1-\pi)bn_1 - (1-\pi)c - \pi c_L) \\
SW^d &= (n_1 + n_2)[a + bn_1 + bn_2 - \pi c_L - (1-\pi)c] \\
SW^o &= n_1(2a + 2bn_1 + bn_2 - c) + n_2(a + bn_1 + bn_2 - c_H)
\end{aligned}
$$

A comparison between the delay and the open-system paths.

Comparing social welfare from the open-system path with social welfare from the delay path, we get the following equation:

$$SW^o - SW^d$$
$$= (a + bn_1)n_1 - \pi(c - c_L)n_1 - (\pi(c - c_L) - (c - c_H))n_2$$

First-generations consumers can enjoy the first-period-flow utility under the open-system strategy, which is denoted by the first term on the right side of the equation. The other terms measure the extra amount of production cost saved by undertaking product R&D instead of process R&D. The sign of $SW^o - SW^d$ can be positive or negative depending on the size of π. SW^o is higher than SW^d if and only if $\pi \leq \bar{\pi} = \frac{(a+bn_1)n_1+n_2(c-c_H)}{(c-c_L)(n_1+n_2)}$. Figure 2 shows the welfare levels from these two paths.

[Figure 2 here]

A comparison between the open-system path and the penetration-pricing path.

$$SW^o - SW^p = 2\pi bn_1 n_2 - (\pi(c - c_L) - (c - c_H))n_2$$

Along both paths, first-generation consumers buy the incumbent's product in period one. The difference is that the entrant undertakes product R&D along the penetration path, while it undertakes process R&D along the open-system path. What is the socially optimal R&D choice, given first-generation consumers' choices? When the entrant undertakes process R&D, it has a positive network effect on first-generation consumers with the incumbent's product. While the social planner takes this effect into account, the entrant does not. Therefore, whenever it is optimal for the entrant to choose process R&D in terms of its profitability, it is also socially optimal. According to (A3), it is optimal for the entrant to undertake process R&D when all first-generation consumers have bought the incumbent's product. Thus, when all of them have bought the incumbent's product, it is also socially optimal for the entrant to undertake process R&D.[19] [20] So, SW^o is higher than SW^p.

[19]According to (A3), $(c - c_H) > \pi(c - bn_1 - c_L)$. It is equivalent to that $\pi bn_1 - (\pi(c - c_L) - (c - c_H)) > 0$. Thus, (A3) implies that $2\pi bn_1 n_2 - (\pi(c - c_L) - (c - c_H))n_2 > 0$.

[20]The incumbent's open-system strategy always attains (weakly) higher welfare level than the penetrating-pricing strategy does no matter whether (A3) holds or not. Suppose

Proposition 2 (a) The open system path attains a higher welfare level than the delay path does if and only if $\pi \leq \bar{\pi} = \frac{(a+bn_1)n_1+n_2(c-c_H)}{(c-c_L)(n_1+n_2)}$. Otherwise, the delay path attains a higher welfare level than the open-system path does.

(b) The open-system path always attains a higher welfare level than does the penetration-pricing path.

Welfare implications of the open system

Next, we analyze the welfare implications of the open system. When π is between $\frac{1}{2}$ and $\frac{a+bn_1}{2bn_2} + \frac{1}{2}$, the incumbent would choose the penetration strategy if it could choose only the closed system. However, when π is higher than $\frac{1}{2}$, the incumbent optimally chooses the open-system strategy. Since the open-system path attains a higher social welfare than the penetration path does, the open-system strategy improves social welfare for these cases.

However, suppose that π is higher than $\max[\frac{a+bn_1}{2bn_2}+\frac{1}{2}, \frac{(a+bn_1)n_1+n_2(c-c_H)}{(c-c_L)(n_1+n_2)}]$.[21] Then the delay path achieves higher social welfare than the open path does. However, the incumbent chooses the open system, and the open system strategy excludes the delay path, while the delay path could be realized under the closed system. Therefore, the open-system strategy lowers the social welfare level, as compared with the closed system. Also, as π grows, the incumbent is more likely to adopt the open-system strategy, and the delay path is more likely to be the most socially efficient outcome.

Proposition 3: *The incumbent's open-system strategy does not always improve social welfare, and we may have a premature market standard under the open system.*

The first-mover advantage

Under the open system, the delay path could be realized when all first-generation consumers wait. We can ask why first-generation consumers do not wait even when the delay path attains the highest social welfare level.

that (A3) does not hold. That is, the entrant optimally undertakes product R&D even when all first-generation consumers have bought the incumbent's product. In this case, even though the incumbent chooses the open system, the following game is exactly the same as that of the closed system subgame, and the incumbent's open-system strategy attains the same social welfare level as the penetration strategy does. Thus, the open system strategy attains weakly higher welfare level than the penetration-pricing strategy does no matter whether (A3) holds or not.

[21] Assumptions (A1) through (A3) do not determine which one is the larger between $\frac{a+bn_1}{2bn_2} + \frac{1}{2}$ and $\frac{(a+bn_1)n_1+n_2(c-c_H)}{(c-c_L)(n_1+n_2)}$.

Consider the following situation: the entrant will succeed in product R&D with probability one, and the improvement of the entrant's technology over the incumbent's is large enough to offset the opportunity cost of consumers' waiting. Hence, it is socially optimal for all first-generation consumers to wait and for the entrant to do product R&D. Do they wait until period two? Not necessarily. The social welfare gain is not transferred to first-generation consumers since the second-period equilibrium price will be set so that a winner beats rivals marginally, but not necessarily low enough to reward consumers for waiting. Even though first-generation consumers pay an opportunity cost of waiting, they must pay an equilibrium price in period two. As long as the entrant cannot make a commitment to a second-period price in period one, there exists a first-mover advantage.

The first-mover advantage exists under both the closed and open systems. However, the uncertainty about the second-period market standard under the closed system may make first-generation consumers wait until the second period, which reduces the negative effect of the first-mover advantage. For instance, for some parameter values, the socially best outcome is realized with the closed system, but the best outcome can be eliminated with the open system because it increases the value of buying the incumbent's product early. That is, the open system may have a premature market standard.

Proposition 4 *The entrant's inability to make a price commitment creates a first-mover advantage.*

Remark*: Excess Inertia*
An interesting issue in the analysis of an industry with networking externalities relates to 'excess inertia': the old standard can 'trap' an industry when a better alternative is available. Katz and Shapiro(1986) find an interesting paradox when two firms promote their own standards. Suppose that product one is cheaper to produce than product two in period one, and that product two is cheaper to produce than product one in period two. They find that the market is biased toward product two: while it is socially better to get product one standardization, we can get product two standardization instead. Katz and Shapiro (1986) call this a second-mover advantage.

However, we show that there exists a first-mover advantage. This different result comes from three different assumptions. Katz and Shapiro (1986) assume that: i) the first-generation consumers cannot wait until period two; ii) firms one and two compete with each other in both periods; and iii) there is

no interim utility, so the consumer's utility depends only on the final network size. Our paper assumes that: i) first-generation consumers can wait until period two; ii) only the incumbent can supply products in period one; and iii) a consumer's total utility consists of each period's flow utility, which depends on each period's network size.

6   Discussion:

Comparison of open systems and licensing contracts

Much of the flavor of this article remains the same for either (pure) open systems or licensing contracts. However, this subsection discusses the difference between licensing contracts with (pure) open systems.

"In the late 1970s, before a standard microprocessor technology had emerged, semiconductor producers typically cross-licensed products with competing companies...The company [Intel] therefore licensed the i8088 and i8086 to 12 competitors and i80286 to 4...The economics of microprocessor production combined with the emergence of the i386 family as the dominant industry standard gave Intel the strategic leverage it needed to change its licensing policies. Beginning with the 386 family, the company refused to grant second-source contracts." [Harvard Business School Case Study 1-292-106, Intel Corporation 1992]

One issue is the feasibility of obtaining a long-term contract. In the Intel case, Intel was willing to license its products only while it was trying to establish them as the market standard. After that, it did not continue to license. In the case where competitors are aware of this and, therefore, do not enter into a licensing contract, the incumbent would ideally like to commit to sharing technologies with others. This long-term contract issue is also related to the fact that it is difficult for us to specify in advance what the technology will be like in the future. For instance, Intel did write a long-term licensing contracts with AMD and IBM. However, there were legal disputes over the interpretations of those contracts. [22]

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[22] AMD lost its licensing for the 386 and beyond, and IBM resolved its dispute by selling its licensing contract to Intel. As a result, Intel does not have any obligation to license its technology for Pentium and onward. For details, see Brandenburger and Nalebuff (1996)

Disputes about the interpretation of licensing contracts on Java Language can be another example.[23] Microsystems claimed that Microsoft modified Java language, acting against the terms of the licensing contract. However, Microsoft claimed that its actions did not violate the agreement. Both sides said they believed that the licensing contract vindicated their positions.

These cases show that it would be difficult to achieve a complete licensing contract. The difference between licensing contracts and open systems are related to the degree of commitment that is possible with each strategy. The open system involves more physical and technical choices in addition to simple contractual ones.

7   Concluding Remarks

In the framework of network effects and durable goods pricing, we explore how the incumbent's system choice changes consumers' expectations, which, in turn, affect the entrant's R&D choice. This paper shows the following results: the incumbent chooses the open system to preempt the entrant's product R&D; the social welfare level under the open system is always higher than under the penetration pricing strategy; and we can have a premature market standard under the open system.

Let us emphasize that the main results are quite robust even when we relax several restrictions of this paper. So far, we have assumed that the incumbent does not undertake R&D activities. Suppose that the incumbent can reduce its unit production cost to c_H by undertaking process R&D. If both the incumbent and the entrant undertake process R&D, their unit production costs become c_H, respectively. To circumvent the zero profit derived by Bertrand competition, we instead assume that when both firms have the same unit costs under the open system, each firm can enjoy some positive profits, $\Pi(c_H, c_H) > 0$. Then, the entrant has an incentive to undertake process R&D under the open system, and we get the same welfare results.

Also, we have assumed that the costs of R&D activities are zero. However, a positive cost of undertaking R&D activities does not change the main results of this paper, as long as the entrant has an incentive to undertakes R&D activities.

[23] "Java and Breach of Contract", New York Times,Oct 16, 1997

A previous version of this paper showed the same qualitative results with two types of consumers. With homogeneous consumers, we can pick up a Pareto dominant equilibrium for consumers. However, with two types of consumers, we need a more refiner equilibrium selection, because these two types of consumers might have differing interests with each other. Since the exposition becomes unnecessarily complicated, we stick to the current model of one type of consumer.

The key is that the entrant faces a trade-off between compatibility and performance in choosing its R&D activity.[24] Most of the welfare results in this paper are driven by the combination of the incumbent's first mover advantage and the entrant's trade-off in R&D choices. As long as we have these two, most of our results are robust.

There are many directions in which the analysis in this paper could be extended. For example, comparing (pure) open systems and licensing contracts would be an interesting future research topic. Another interesting topic is the role of pre-announcements by firms on R&D competition. The first-mover advantage in this paper is created by the entrant's inability to make a price commitment. Usually, firms make pre-announcements about products under development. It would be interesting to analyze a dynamic R&D game with pre-announcements (or Vaporware) when consumers have an option to wait.

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[24]Chapter 7 in Shapiro and Varian (1998) describes how firms face the tradeoff between compatibility and performance in their R&D choices.

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<**Appendix**>

Lemma 1: *All current consumers buy products from only one firm in period two. When product R&D fails, all current consumers buy the incumbent's product at $c + bI_I(1)$. When product R&D succeeds, all current consumers buy the entrant's product at $c - bI_I(1)$.*

Proof. Given $I_I(1)$, p_2 and r_2, there are multiple equilibria because of positive network effects. According to the equilibrium selection, choices by current decision-making consumers are made as if they could coordinate their choices. That is, if there is one Pareto dominant equilibrium over others for the decision-making consumers, the Pareto dominant equilibrium is realized.

We will find the Pareto dominant equilibrium in the following way. First, we will find a set of consumers choices in which each consumer gets the highest payoff. Then we will check whether the consumers' choices constitute Nash Equilibrium in the subgame. If so, the NE is Pareto dominant for the consumers and, therefore, is a unique equilibrium consistent with the equilibrium selection.

First, let us find a set of consumers' choices in which each consumer gets the highest payoff. Because of positive network effects, it is necessary for all current consumers to choose the same product in order to achieve the highest payoff. If all current consumers buy the incumbent's product, they each get $a + b(n_1 + n_2) - p_2$. If all of them buy the entrant's products, they each get $a + b(n_1 + n_2 - I_I(1)) - r_2$. If $p_2 - bI_I(1)$ is less than r_2, each consumer gets the highest utility by buying the incumbent's product.

Let us check whether it is NE for all consumers to buy the incumbent's product when $p_2 - bI_I(1)$ is less than r_2. If a consumer deviates to the entrant's product, she gets $a - r_2$. Therefore, if $p_2 - bI_I(1)$ is less than r_2, none has an incentive to deviate. Thus, if $p_2 - bI_I(1)$ is less than r_2, it is a unique NE consistent with the EQ selection for all active consumers to buy the incumbent's product.

Using the same logic, if $p_2 - bI_I(1)$ is higher than r_2, current consumers get the highest payoff by buying the entrant's product together. Moreover, none has an incentive to deviate. Thus, if $p_2 - bI_I(1)$ is higher than r_2, it is a unique NE consistent with the EQ selection for all active consumers to buy the entrant's product.

Both firms are willing to lower their price as low as their marginal costs. When product R&D is successful, the entrant's unit production cost is lower than $c - bI_I(1)$, and only the entrant sells its product at $r_2 = c - bI_I(1)$. When product R&D fails, both firms have the same unit production cost. However, because of the advantage from its installed base, only the incumbent sells its product at $p_2 = bI_I(1) + c$. ∎

Lemma 2: *There is a unique SPNE consistent with the equilibrium selection. If p_1 is lower than or equal to $a + bn_1 + c - \pi_2 bn_2$, all first-generation consumers buy the incumbent's product in period one. Otherwise, they wait until period two.*

Proof. As we did in Lemma 1, we will find a set of consumers' choices in which each current consumer gets the highest payoff, given p_1. Then we will check whether the consumers' choices constitute SPNE. If so, the equilibrium is the unique one consistent with the equilibrium selection.

First, let us find a set of consumers' choices in which each current consumer gets the highest payoff.

If a consumer buys the incumbent's product, her expected utility is $a + bI_I(1) + a + E(bI_1(2)) - p_1$. The size of $I_1(2)$ depends on the R&D result:

If the entrant's R&D fails, $I_1(2)$ will be $n_1 + n_2$. If the R&D is successful, $I_1(2)$ will be $I_I(1)$. Thus, the expected utility from buying the incumbent's product in period one is $a + bI_I(1) + a + (1 - \pi)b(n_1 + n_2) + \pi bI_I(1) - p_1$, which increases with $I_I(1)$

Suppose that a consumer wait until the second period. Then, she will buy the incumbent's product in period two at $c + bI_I(1)$ if the entrant's R&D fails. If the entrant's R&D is successful, she will buy the entrant's product in period two at $c - bI_I(1)$. So her expected utility from waiting until period two is $a + b(n_1 + n_2) - (1 - \pi)bI_I(1) - c$, which decreases with $I_I(1)$.

Since the consumer's expected utility from buying the incumbent's product increases with $I_I(1)$, and the expected utility from waiting decreases with $I_I(1)$, the (potentially) highest utility for a first-generation consumer is obtained either when all first-generation consumers buy together or when they all wait together.

When all the first-generation consumers buy the incumbent's product in period one together, the expected utility is $a + bn_1 - p_1 + a + bn_1 + (1 - \pi)bn_2$. When all of them wait until period two, the utility from waiting is $a + bn_1 + bn_2 - c$. Therefore, if p_1 is less than or equal to $a + bn_1 - \pi bn_2 + c$, all first-generation consumers get the highest payoff among all potential outcomes by purchasing the incumbent's product together in period one. Moreover it is a SPNE since no first-generation consumer has an incentive to deviate. Therefore, it is the unique SPNE consistent with the equilibrium selection that all first-generation consumers buy the incumbent's product if $p_1 \leq a + bn_1 + c - \pi_2 bn_2$.

Using the same logic, if p_1 is higher than $a + bn_1 + c - \pi_2 bn_2$, all first-generation consumers achieve the highest payoff by waiting. Moreover, it is an SPNE since none has an incentive to deviate. Therefore, it is the unique SPNE consistent with the equilibrium selection that all first-generation consumers wait until period two if $p_1 > a + bn_1 + c - \pi_2 bn_2$. ∎

Lemma 5: *There is a unique SPNE consistent with the equilibrium selection. If p_1^o is lower than or equal to $a + bn_1 + c_1$, all first-generation consumers buy the incumbent's product, expecting that their purchase will induce the entrant to adopt the incumbent's technology. Otherwise, they will wait until period two.*

Proof. As we did in Lemma 1, for a given p_1^o, we will find a set of consumers' choices in which each current consumer gets the highest payoff. Then we will

check whether or not the consumers' choices constitute SPNE. If so, the equilibrium is the unique one consistent with the equilibrium selection.

First, let us find a set of consumers' choices in which each current consumer gets the highest payoff.

If $I_I(1)$ is less than $\bar{I}$, then the following subgame is the same as the closed system with $I_I(1)$. The expected utility from buying the incumbent's product is $a+bI_I(1)+a+(1-\pi)b(n_1+n_2)+\pi bI_I(1)-p_1^o$, which increases with $I_I(1)$. If $I_I(1)$ is larger than $\bar{I}$, then in the following subgame, the entrant will undertake process R&D, and the incumbent's and the entrant's products are compatible with each other. The expected utility from the incumbent's product is $a + bI_I(1) + a + b(n_1 + n_2) - p_1^o$. Thus, the expected utility from buying the incumbent's product is maximized when $I_I(1) = n_1$.

Suppose that a consumer waits until the second period. If $I_I(1)$ is less than $\bar{I}$, the expected utility from waiting until period two is $a + b(n_1 + n_2) - (1-\pi)bI_I(1)-c$, which decreases with $I_I(1)$. If $I_I(1)$ is larger than $\bar{I}$, then the utility from waiting until period two is $a + b(n_1 + n_2) - c$, which is constant.

Therefore, if p_1^o is less than $a + bn_1 + c$, the first-generation consumers get the highest payoff among all potential outcomes when all of them buy the incumbent's product together. Moreover, no first-generation consumer has an incentive to deviate when all of them buy it. Thus, if p_1^o is less than $a + bn_1 + c$, it is the unique SPNE consistent with the equilibrium selection for all first-generation consumers to buy the incumbent's product.

Using the same logic, if p_1^o is higher than $a + bn_1 + c$, the first-generation consumers get the highest payoff when all of them wait together. Moreover, no first-generation consumer has an incentive to deviate. It is the unique SPNE consistent with the equilibrium selection that all of the first-generation consumers wait until period two. ∎
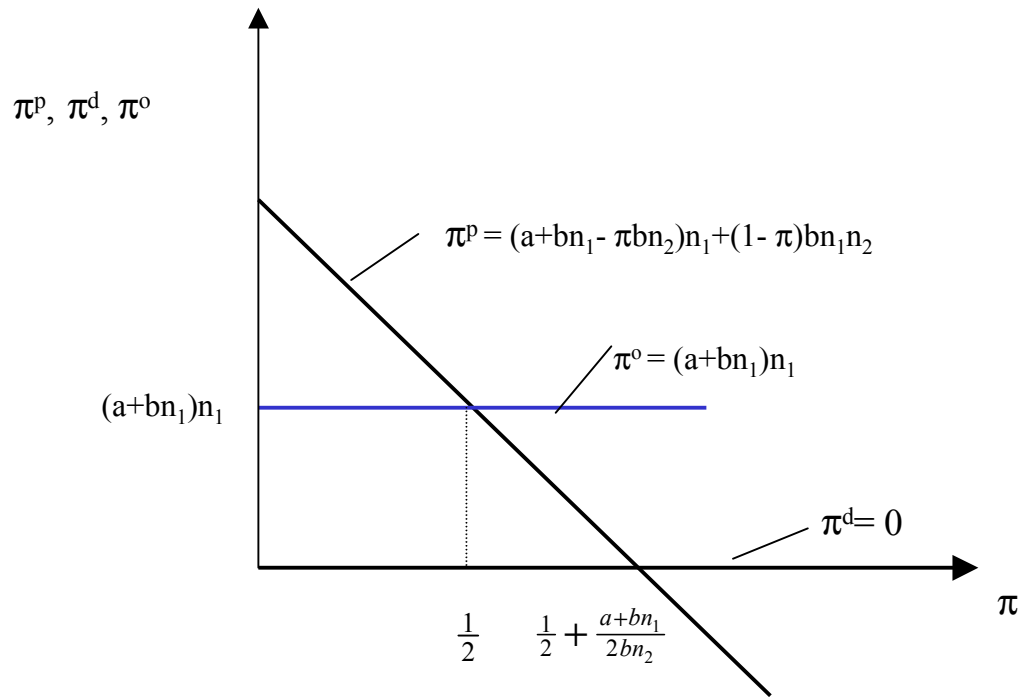
Figure 1. Profit levels under the penetration, the delay and the open system cases.

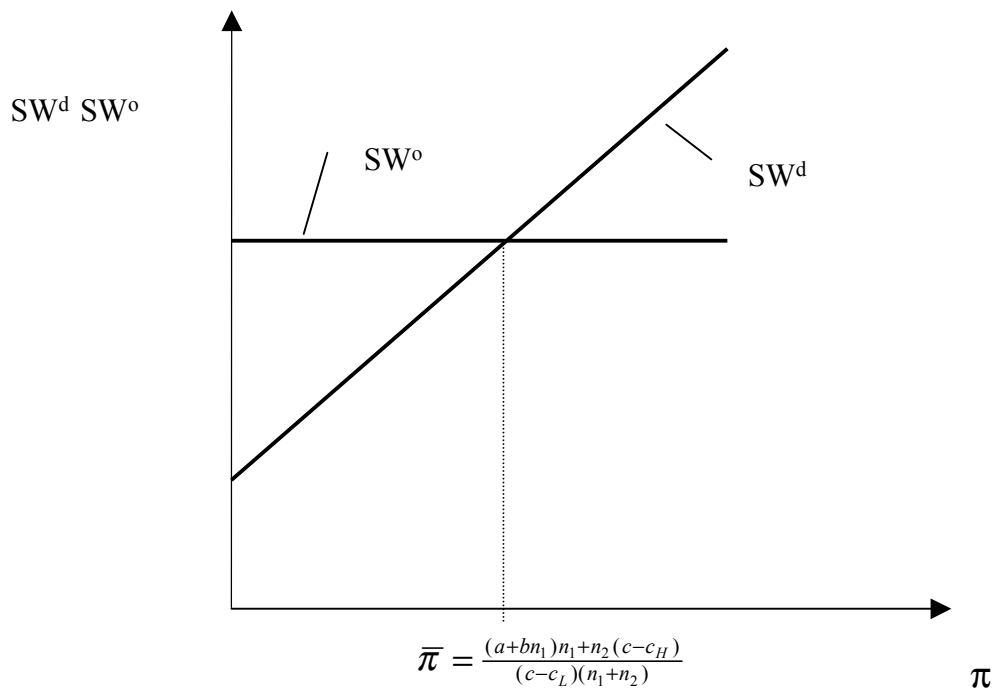$$\overline{\pi} = \frac{(a+bn_1)n_1 + n_2(c-c_H)}{(c-c_L)(n_1+n_2)}$$

Figure 2. Social welfare levels under the delay and the open-system paths.