Adoptions and Orphans in the Early Microcomputer Market:

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Abstract

In this paper we develop a model with (1) differentiated consumers, (2) endogenous adoption times, (3) technical uncertainty, and (4) alternative technologies sponsored by competing vendors. We identify conditions under which orphaning arises endogenously in a framework of dynamic competition. We then use the model to examine the development of the microcomputer market in the early 1980s, when the orphaning of a widely-adopted operating system occurred. We find that the data characterizing this event are consistent with our theoretical framework.

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1 Introduction

Technical change in competitive economies is characterized by cycles of creative destruction. Users adopt new products and abandon others. In this paper we examine the relationship between adoption of technologies and the phenomenon of “orphaning." Orphaning occurs when late users adopt a technology incompatible with the technology adopted by early users, and suppliers of supporting services (complementary products) cease to provide their products for the old technology. These issues are of concern to vendors and users in electronics markets where technical standards and product designs are fluid. Recent examples include (1) personal computer operating systems (CP/M was the early de facto standard and was subsequently replaced by MS-DOS), (2) videocassette recorders (Betamax versus VHS), and (3) Stereo systems (Digital Compact Cassettes versus the SONY Minidisk and Cassettes versus 8-track tapes). In all of these examples, the technologies were incompatible, that is, supporting services or software written for one system did not work on the other system.

In this paper we develop a model with (1) differentiated consumers, (2) endogenous adoption times, (3) technical uncertainty, and (4) alternative technologies sponsored by competing vendors. We identify conditions under which orphaning arises endogenously in a framework of dynamic competition.

Our theoretical analysis contains several insights about the factors producing orphans. We show that orphaning occurs in part, because of the heterogeneity in consumer evaluations. In particular, our model generates a diffusion process in which high value users are the first to adopt new technologies. Uncertainty regarding the availability of complementary software also plays a key role. Early and late buyers are likely to make different choices when there are significant changes in the availability of complementary services over time. Finally, competition plays a role in discouraging orphaning; intense competition among vendors translates into lower prices in the present, and encourages early adoption by all groups.

In the second part of the paper, we use the model to analyze data on the micro-computer market in the early 1980s, when most of the original operating systems technologies were orphaned. In particular, we examine the role played by increases in the availability of software and peripherals for the competing platforms. These increases were viewed as far from certain at the time and played a significant role in the orphaning process. We find that in contrast to CP/M, the success of MS-DOS largely revolved around the significant provision of DOS compatible application software programs. The data are consistent with our theoretical framework.

1.1 Related Literature

Our paper adds to an already sizeable literature on platform competition and technology adoption. In a departure from the literature, our analysis of platform competition is both theoretical and empirical; the empirical portion builds on previous studies of the microcomputer industry. Gabel [1991] and Langlois and Robertson [1992] provide an extended economic history of the personal computer industry. The latter identify factors leading to open platforms in the long run, while the former is a detailed case study concerning the role of *de facto* standardization on the evolution of the microcomputer industry. In contrast to these two studies, our empirical work is quantitative rather than descriptive. Our empirical analysis also builds on Bresnahan and Greenstein [1992], who characterize platform competition in the first three decades of the computer industry. They identify the factors determining outcomes in platform competition. Our work differs in that we provide a formal theoretical analysis of competition between "open" platforms and we employ an original data set to perform the empirical analysis.

Our theoretical analysis of platform competition resembles in spirit two dynamic models by Katz and Shapiro of technological adoption in the presence of network externalities.[1] Katz and Shapiro [1986] investigate whether the market, by adopting one of two competing

[1] Other dynamic models of technology adoption in the presence of network externalities include Farrell and Saloner [1986] and Arthur [1989]. In both of these models, consumers purchase at different dates from *competitive* firms.

incompatible technologies, in both periods of a two period model, establishes a de facto standard. They show that an emerging (superior) technology is overadopted, ie, is adopted for parameter values for which it is socially optimal to adopt the other technology. In Katz and Shapiro [1992], an entrant must decide when to enter and whether to make its product compatible with that of the incumbent. They show that when an entrant chooses to make its product incompatible, it enters earlier than the socially optimal date. Further there is suboptimal standardization.

Our model makes departures both in structure and focus. The common theme of the Katz and Shapiro papers is an examination of the social and private incentives to obtain compatibility, that is, standardization. In contrast, we focus on understanding conditions under which different types of consumers purchase different systems at different dates, which an explicit model of adoptions and orphans requires. Hence, we place importance on the uncertainty about the development of complementary software for the incompatible technologies and consumer heterogeneity. In addition, we tailor our analysis to fit conditions in the PC market. This enables us to statistically analyze historical data from this market and compare the results with our theoretical framework.

A related series of papers examine technological adoption in the presence of *indirect network externalities*, that is, when the link between the number of users occurs through the variety of compatible software products. See Chou and Shy [1990] and Church and Gandal [1992,1993]. Similar to these settings, we also examine how complementary products affects both vendor and buyer decision-making. Again, our theoretical focus differs. In Chou and Shy and Church and Gandal, all consumers make adoption decisions simultaneously. Hence orphaning cannot arise in equilibrium in their models.

Finally, we overlap with the themes found in several decision-theoretic papers of investment under uncertainty. Sanchez [1994], and Dixit and Pindyck (1994) consider a setting under which firms make discrete and irreversible investments in emerging technologies under uncertainty. Orphaning occurs exogenously in their models, and buyers take action in anticipation of it. Although we embed similar buyer behavior in our analysis, we focus on how the interaction between buyers and sellers can produce orphaning in equilibrium.

In the following section, we develop the basic model. Sections 3 & 4 characterize equilibria for the basic model. In sections 5 & 6, we enrich the model. Sections 7 & 8 provide anecdotal and statistical evidence consistent with our theoretical model. Section 9 provides brief conclusions.

2 The Basic Model

We develop a simple two-period model in which two firms offering incompatible systems (supporting services or software written for one system will not work on the other system) compete for sales. Each system will, with a positive probability, experience some innovation; by innovation, we mean the development of supporting services or complementary “software" which increases the value of the system.[2]

There are two types of consumers, denoted “techies" (T) and “non-techies" (N), and a probability of innovation which is independent of the number of early users.[3] The key features of the model are that (1) a system is durable, i.e., a system purchased in the first period will also provide service in the second period, (2) either, neither, or both systems can experience innovation (between the two periods) which will enhance the value of the systems, and (3) consumers can defer their purchase decisions to see the outcome of the innovation, if any. For analytical simplicity, we assume that consumers can make at most one purchase, and that this purchase can occur in either of the two periods.[4]

We make the following assumptions:

[2]Supporting services can take the form of application software, peripheral devices, retail service, distribution facilities and information and literature about the products.

[3]In section 4, we extend the basic model to the setting in which the probability of innovation depends on the number of early users.

[4]In section 6, we show that are results are robust to the setting in which early adopters can abandon the system they purchased in the first period and buy a different system in the second period.

(1) The value techies (non-techies) derive in each period from a system without any innovation is θ^T (θ^N). We let N^j denote the number of consumers of type $j, j = T$ or N. $N \equiv N^T + N^N$.

(2) $\theta^T > \theta^N > 0$, that is, techies derive more “standalone" utility from the basic system than do non-techies.

(3) The systems have identical marginal costs of production in each period (This is for ease of exposition and can be relaxed). The first period marginal costs for both technologies are denoted c_0 and the second period marginal costs are denoted c_1. We assume that the marginal costs either fall or remain constant over time, i.e., $c_0 \geq c_1$. For the case in which costs remain constant over time, we denote the common marginal cost by c.

(4) Each consumer purchases at most one system.

(5) A consumer of type $j = N$ or T that purchases system $i = a, b$ in the initial period (T=0) receives expected utility over the two periods equal to

$$V_i^j = 2\theta^j + \rho_i U_i - p_i^0, \tag{1}$$

where ρ_i is the probability that system i experiences innovation and U_i is the added utility either type of consumer derives from system i should innovation occur, and p_i^0 is the price charged by firm i in the initial period.

If a consumer of type j waits until the final period (T=1) and then purchases system i, the utility derived is $V_i^j = \theta^j + U_i - p_i^1$ if innovation occurs, and $V_i^j = \theta^j - p_i^1$, if there is no innovation, where p_i^1 is the price charged by firm i in the final period.

Recall that innovation means the development of supporting services or complementary “software" which increases the value of the system. In our model, the U_i's represent the increase in value that comes from the increase in the *availability* of complementary software, rather than the actual consumption of the software.

(6) For ease of notation, let $\Delta U \equiv U_a - U_b$ denote the difference in value added by complementary software for the two systems. Without loss of generality we assume $\Delta U \geq 0$, i.e., system “a" is *ex post* superior. The interpretation is that if complementary software indeed becomes available for both systems, the value of system “a" is enhanced by more than the value of system “b."

Finally, we introduce some notation:

Let $\delta \equiv (\delta^N, \delta^T)$ denote the initial period purchasing decisions of the two types, where $\delta^j = i$ indicates type j purchased system $i = a, b$ in the initial period. $\delta^j = 0$ denotes the state in which type j consumers make no purchase in the initial period.

Further, let $\alpha \equiv (\alpha_a, \alpha_b)$ denote whether innovation occurred, ie, whether complementary software, appeared between the initial and final periods.

In the following two sections, we consider two cases. In the first case (section 3), the equilibrium is always characterized by early adoption, that is, for all parameter values, all consumers purchase in the initial period. In the second case (section 4) , outcomes in which non-techies do not purchase in the initial period are possible. In both cases, if consumers make a purchase in the first period, they always purchase the ex ante superior system. The motivation behind these sections is to establish conditions in which some consumers wait and early purchasers are orphaned.

3 Early Adoptions

Here we consider a special case under which all consumers will purchase the ex ante superior system in the first period, despite the uncertainty. This case obtains even when the potential benefits from innovation (the U_i's) are large. The intuition is that competition between the systems for ex ante purchases leads to relatively low initial period prices. This case obtains under the following two assumptions:

- Marginal costs are identical in both periods.
- The standalone value of a system exceeds the marginal cost of production for both types of consumers.

Recall that in this case c denotes the constant per period marginal costs. Thus the second condition above becomes $\theta^N > c$. To find equilibrium prices and purchase decisions, we work backwards starting with the last period.

3.1 Last Period (T=1) Pricing.

Since α can assume four values and δ can assume nine values, there are thirty-six cases. Fortunately, the analysis simplifies considerably. First note that if $\delta = (a,a),(a,b),(b,a)$ or (b,b), so that all consumers made purchases in the initial period, final period prices are irrelevant. The following lemma shows that there are effectively four cases.

Lemma 1 *(i) If both firms innovated between the initial and final periods, i.e.,* $\alpha = (1,1)$ *and if* $\delta \in \{(a,0),(b,0),(0,b),(0,a),(0,0)\}$*, i.e., some consumers made no purchase in the initial period, then equilibrium last period prices are* $p_a^1 = \Delta U + c$ *and* $p_b^1 = c$.

(ii) When $\alpha = (1,0)$*, and* $\delta \in \{(a,0),(b,0),(0,b),(0,a),(0,0)\}$*, then equilibrium last period prices are* $p_a^1 = U_a + c$ *and* $p_b^1 = c$.

(iii) When $\alpha = (0,1)$*, and* $\delta \in \{(a,0),(b,0),(0,b),(0,a),(0,0)\}$*,* $p_a^1 = c$ *and* $p_b^1 = U_b + c$.

(iv) When $\alpha = (0,0)$*, and* $\delta \in \{(a,0),(b,0),(0,b),(0,a),(0,0)\}$*,* $p_a^1 = c$ *and* $p_b^1 = c$.

Further, the expected utility of waiting for a consumer of type j is

$$EV^j = \theta^j + \rho_a \rho_b U_b - c. \tag{2}$$

Proof: The equilibrium prices in cases (i) - (iv) are straightforward. A consumer of type j will derive utility net of price paid of $\theta^j - c$ in cases (ii)-(iv); in case (i) a consumer receives net utility of $\theta_j + U_b - c$. Since case (i) occurs with probability $\rho_a \rho_b$, the expression EV^j follows immediately. ■

We will employ (2) to determine whether a consumer of type j will buy one system or the other given any pair of prices in the initial period $p^0 \equiv (p_a^0, p_b^0)$.

3.2 Equilibrium Initial Period (T=0) Pricing

Suppose, system h is ex ante superior, that is, $\rho_h U_h \geq \rho_j U_j$, for $h, j = a$ or b, and $h \neq j$. Recall we assume that $\Delta U \equiv U_a - U_b \geq 0$. When $\rho_b U_b \geq \rho_a U_a$, it must be the case that system “b" has a higher probability of experiencing innovation than does system “a." Although system “a" would dominate system “b" when both have software, it is possible for system “b" to be ex ante superior.

A consumer of type j will prefer purchasing system “b" to system “a" in the initial period, period 0, if and only if $2\theta^j + \rho_a U_a - p_a^0 < 2\theta^j + \rho_b U_b - p_b^0$ or iff $p_a^0 - p_b^0 > \rho_a U_a - \rho_b U_b$.

When $\rho_a U_a < \rho_b U_b$, all consumers prefer system “b” to system “a” in the initial period whenever firm “b’s" price, p_b^0, is less than $\rho_b U_b - \rho_a U_a + c$, and the price charged by firm “a” is equal to marginal cost c. Conversely, when $\rho_a U_a > \rho_b U_b$, all consumers will prefer system “a” to system “b” in the initial period, whenever $p_a^0 \leq \rho_a U_a - \rho_b U_b + c$ and $p_b^0 \geq c$.

The question remains as to whether consumers will purchase in the first period or wait. The following proposition shows that in this case, competition induces all consumers to buy in the initial period.

Proposition 1 *(Early Adoption) Suppose $\theta^N > c$. The unique subgame prefect equilibrium is characterized by*

$$p_a^0 = \max\{-\Gamma + c, c\} \;\; \textit{and} \;\; p_b^0 = \max\{\Gamma + c, c\},$$

where $\Gamma \equiv \rho_b U_b - \rho_a U_a$. All consumers buy the same system in the first period and from the firm that has the ex ante superior system, i.e., from firm “a" iff $\rho_a U_a \geq \rho_b U_b$.

Proof: First notice that price competition between the two firms will drive first period prices to $p_a = c$ and $p_b = \Gamma + c$ or $p_a = -\Gamma + c$ and $p_b = c$; the firm with the ex ante superior system makes all the sales and its rival has zero sales and profits.

If the firm with positive sales were to delay selling until the last period - in hopes of earning greater profits - then its rival would sell to all consumers in the initial period. Thus, the firm with the ex ante superior system will not be able to earn more by setting an initial period price above $|\Gamma| + c$ (and possibly delaying sales).

Further, the firm with the ex ante superior system will earn less if its initial period price is less than $|\Gamma| + c$. A best response for its rival to a first period price of $|\Gamma| + c$ is to set its initial period price at c.

We now show that when initial period prices are $|\Gamma| + c$ and c, both types of consumers will purchase early rather than wait. First suppose that system "b" is ex ante superior. Then the expected utility for a consumer of type j buying system "b" in period 0 is

$$2\theta^j + \rho_b U_b - \Gamma - c = 2\theta^j + \rho_a U_a - c.$$

Now suppose that system "a" is ex ante superior. Then the expected utility for a consumer of type j buying system "b" in period 0 is

$$2\theta^j + \rho_a U_a + \Gamma - c = 2\theta^j + \rho_b U_b - c.$$

Since both of the above utilities are greater than the expected utility from waiting from (2), all consumers purchase in the initial period. ■

The above proposition indicates that competition will induce both types of consumers to buy early from the same firm, whenever standalone system values (θ^N and θ^T) are relatively large for both types of consumers and when production costs are not declining over time.

4 Waiting Games

Here we consider a more general model, in which we relax the assumptions we made in the previous section. We consider the case in which marginal costs fall over time, while maintaining the assumption that stand-alone system values exceed the latter period marginal costs for all consumers. In the Appendix we formally examine a qualitatively similar, but algebraically more tedious, case in which "non-techie" preferences are such that will not purchase a system without complementary software at any price which covers marginal production costs, but would be willing to pay a positive price for either system if software were to become available.

When marginal production costs initial period are c_0 and fall over time to c_1 in the final period, two outcomes are possible:

1. All consumers purchase the ex ante superior system in the initial period.

2. Techies purchase the ex ante superior system in the initial period. Non-techies purchase in the final period.[5]

In the second outcome, techies get can stuck with orphan technologies depending on which system experiences innovation. The reason non-techies wait is that the firm with the ex ante superior system cannot price discriminate among consumers in the initial period. When costs fall significantly, this firm would prefer to sell only to techies than to set price so low as to attract both techies and non-techies. Whence adoptions and then orphans!

Proposition 2 *Suppose that* $c_0 - c_1 - \rho_b(1 - \rho_a)U_b \leq \theta^T$.

(I) In the case in which system A is both ex post superior and ex ante superior so that $\rho_a U_a > \rho_b U_b$ *there is a unique equilibrium in which:*

1. *All consumers purchase system "a" early if* $\theta^N \geq c_0 - c_1 - \rho_b(1 - \rho_a)U_b$. *Initial period prices are* $p^0 = (c_0 - \Gamma, c_0)$.

2. *For* $\theta^N < c_0 - c_1 - \rho_b(1 - \rho_a)U_b \leq \theta^T$, *techies purchase the ex ante superior system in the initial period. Non-techies purchase in the final period. Initial period prices are* $p^0 = (c_0, c_0 + \Gamma)$.

[5]In the case we consider in the appendix, an additional (third) outcome in which techies purchase the ex ante superior system in the first period and non-techies make never purchase is possible. In outcomes 2 and 3, techies getting stuck with orphan technologies. The only qualitative difference between the case of falling costs and the case we consider in the appendix is that in the former, non-techies eventually always make a purchase. In the latter case, if non-techies have low stand-alone valuations and neither system experiences an innovation, they will make no purchases.

(II) In the case in which the ex post superior system is inferior ex ante there is a unique equilibrium in which:

1. *All consumers buy early from the ex ante superior system if* $\theta^N \geq c_0 - c_1 - \rho_a(U_a - \rho_b U_b)$. *Initial period prices are* $p^0 = (-\Gamma + c_0, c_0)$.
2. *For* $\theta^N < c_0 - c_1 - \rho_a(U_a - \rho_b U_b) \leq \theta^T$, *techies purchase the ex ante superior system in the initial period. Non-techies purchase in the final period. Initial period prices are* $p^0 = (-\Gamma + c_0, c_0)$.

Proof: We first prove the result for case when the ex ante superior system is also superior ex post, that is, for $\Gamma = \rho_b U_b - \rho_a U_a < 0$ and $U_a \geq U_b$. Suppose that the techies buy the ex ante superior system in the first period. We will show later that this will be true in equilibrium.

Suppose the initial period price for system a is $p_a^0 = -\Gamma + c_0$, and the initial period price for system b is $p_b^0 = c_0$. Note that if all consumers buy early, the fact that there is price competition and the difference in expected values of the two systems is Γ implies that these would have to be the first period equilibrium prices. If firm A were to raise its price, firm B, which otherwise would not make any sales, could then charge a positive price and earn profits.

Given these prices, the expected utility of non-techies from buying early is

$$\rho_a U_a + 2\theta^N - (-\Gamma + c_0) = \rho_b U_b + 2\theta^N - c_0.$$

If the non-techies wait, from Lemma 1, they receive an expected utility of $\theta^N + \rho_a \rho_b U_b - c_1$.

Comparing the above two equations, buying early yields higher utility for non-techies at prices $-\Gamma + c_0, c_0$ whenever

$$\theta^N \geq c_0 - c_1 - \rho_b(1 - \rho_a)U_b.$$

So for θ^N exceeding the above critical value, all consumers (techies and non-techies) alike purchase system A, the ex ante superior system, in the first period.

Now consider the case in which θ^N is below the above critical value. If firm A wants to sell to both types in the first period, then it must set p_a^0 low enough to attract non-techies. Following the same argument used in Proposition 2, the maximum price that firm A can charge and sell to both cohorts is

$$p_a^0 = \rho_a(U_a - \rho_b U_b) + \theta^N + c_1.$$

The profits from selling to all consumers in the first period when θ^N is below the above critical value are $N[p_a^0 - c]$ and the expected profits from selling only to the techies in the first period are

$$-N^T\Gamma + N^N[\rho_a(1-\rho_b)U_a + \rho_a\rho_b(U_a - U_b)],$$

where the second term represents the expected profits from selling to non-techies in the second period. The profits to selling to both types are larger whenever

$$\theta^N \geq c_0 - c_1 - \frac{N^T(\rho_b(1-\rho_a)U_b)}{N}$$

.

Since this critical value exceeds the above critical value, part (I) of the proposition follows immediately. The proof of part (II) is analogous and hence omitted. ∎

As in Proposition 1, competition drives initial period prices down to (or just below) the point at which the firm with the ex ante inferior system could make sales and earn zero profits. These prices will induce techies to buy the ex ante superior in the initial period.[6]

The proposition shows that non-techies will not purchase in the initial period when (1) the fall in marginal cost $(c_0 - c_1,)$ is large relative to the standalone value, θ^N, (2) the probability that the ex ante superior system will experience innovation is high relative to the probability

[6]Note that when $\theta^T < c_0 - c_1 - (1-\rho_a)\rho_b U_b$, a third case in which techies also wait obtains. We are using a discrete time model to approximate what are essentially continuous time events. So we simplify the choice of adoption dates to either early or late, and therefore we have restricted attention to cases in which at least techies will buy early.

that the ex ante inferior system will experience innovation, and (3) the additional utility U_i associated with the introduction of complementary products for the ex ante inferior system is low relative to the additional utility associated with the ex ante superior system. Clearly (1) is obvious, that is large decreases in marginal costs encourage low-value consumers to delay purchases; on the other hand, (2) and (3) may seem surprising. The intuition is that under these conditions, the ex ante superior system is much more attractive than the ex ante inferior system and hence there is not intense price competition between the systems; in such a case, it is optimal for non-techies to wait.

Part II of Proposition 2 shows that under the above conditions, early and late buyers will make different choices when there are significant changes in the availability of complementary services over time.

5 Network Externalities

In Propositions 1 and 2, the probabilities of innovation (the ρ's) are independent of the number of consumers who purchase each product in the initial period. Our interpretation of innovation is the appearance of complementary products, such as software. The incentives of third parties to develop software may depend on the number of early adopters. In this section, we consider the case when the probabilities of innovation are increasing functions of the number of initial period adopters, that is, there are direct network externalities. For simplicity, we again consider the basic case in which marginal costs are constant over time. We consider network externalities of the form

$$\rho_i = \rho_i(N_i), \quad i = a, b. \tag{3}$$

where $\frac{\partial \rho_i}{\partial N_i} \geq 0$. When there are direct network externalities, multiple equilibria can exist, as the following proposition illustrates:

Proposition 3 *Suppose that*

(1) $\theta^N > c$,

(2) $\rho_a(N)U_a > \rho_b(0)U_b$, and

(3) $\rho_b(N)U_b > \rho_a(0)U_a$,

where N is the number early adopters.
(I) An equilibrium in which all consumers adopt system “a" in the initial period exists. Equilibrium prices are $p_a^0 = \rho_a(N)U_a - \rho_b(0)U_b + c$, and $p_b^0 = c$.

(II) An equilibrium in which all consumers adopt system “b" in the initial period exists. Equilibrium prices are $p_b^0 = \rho_b(N)U_b - \rho_a(0)U_a + c$, and $p_a^0 = c$.

Proof: In the first equilibria, everyone, both firms and each individual consumer, anticipates that consumers will purchase system “a." These beliefs are self-fulfilling, provided that firm “a" sets its price at $p_a^0 = \rho_a(N)U_a - \rho_b(0)U_b + c$. In the second equilibria, everyone (correctly) anticipates that early adopters will purchase system “b." These beliefs are self-fulfilling, provided that firm “b" sets its price at $p_b^c = \rho_b(N)U_b - \rho_a(0)U_a + c$. Then, the result follows immediately from Proposition 1. ■

Hence the result is as characterized in Proposition 1, with the exception that there are multiple equilibria.

6 Second Purchases

Here we consider the case in which early period adopters can purchase the other hardware technology in the final period. We illustrate that the possibility of re-purchase has no qualitative effect on the equilibrium outcomes characterized in Proposition 2. We consider the case in which technology A is both ex ante and ex post superior and only techies made initial period purchases.

The techies’ final period utility of staying with the early period system *a* is $\theta^T + \alpha_a U_a$, while the utility of switching to system “b" is $\theta^T + \alpha_b U_b - p_b^1$. Since technology “a" is ex post superior, the techies would not switch to technology “b" in cases $\alpha = (0, 0)$, $\alpha = (1, 0)$, and $\alpha = (1, 1)$) at any non-negative price. Hence the equilibrium final period prices are as characterized in Lemma 1 with "c" replaced by "c_1." For the case in which $\alpha = (0, 1)$, the techies might make an additional purchase.

Lemma 1 shows that when re-purchase is not possible, the equilibrium final period prices in case $\alpha = (0, 1)$ are $p^1_a = c_1$ and $p^1_b = U_b + c_1$. Notice that at these prices, only non-techies would purchase in the final period. If firm "b" charged $p^1_j \leq U_b$, techies would indeed make a second purchase. Thus if $N(U_b - c_1) < N^N U_b$, so that it is not profitable for firm "b" to sell to both cohorts, final period prices are identical to those characterized by Lemma 1, and no re-purchase occurs despite the fact that re-purchase is possible. Thus, the expected utility of waiting does not change for any type. If on the other hand, it is profitable for firm "b" to sell to both cohorts, final period prices are $p^1_b = U_b$ and $p^1_a = c$. Here, the expected utility of waiting for non-techies increases by the factor of $\rho_b(1 - \rho_a)c_1$.

Alternatively, if price discrimination (based on whether a consumer already has an "old" product) is feasible, consumers (techies) who turned in their "old" systems would be charged $p^1_b = U_b$ and $p^1_a = c_1$, while consumers who did not turn in an old system would be charged $p^1_b = U_b + c_1$ and $p^1_a = c_1$. In the case of price discrimination, the expected utility of waiting does not change for any type, regardless of the distribution of techies in the population.

Hence the equilibrium is as characterized in Proposition 2, with the exception that techies may make multiple purchases. We conjecture that this argument generalizes to other cases.

In summary, our theoretical analysis contains several insights about the factors producing orphans. Orphaning occurs in part, because of the heterogeneity in consumer evaluations, ie., high value users are the first to adopt new technologies. However, uncertainty regarding the availability of complementary software also plays a role. Proposition 2 shows that early and late buyers will make different choices when there are significant changes in the availability of complementary services over time. Finally, competition plays a role in encouraging early adoption by all groups, which should discourage orphaning.

7 Platform competition in the micro computer market

It is not our intention to recount the economic history of the personal computer industry.[7] Here we explain how our model captures many of the factors that shaped a key episode of platform competition, between the CP/M and DOS operating systems that occurred in the early 1980s.

There were a number of other operating systems that competed with CP/M and DOS in that period, most notably Apple, as well as Unix, TRS, and Atari. The evidence (see Figures 1-3) suggests the preeminence of the fully open platforms, CP/M, MS-DOS, and partially-open Apple platforms. However, Apple appeared to serve a different market than did CP/M and DOS (See Gabel [1991], and Langlois [1992]).[8]

Before we begin our discussion we briefly explain our data, which we assembled for this study. Figures 1-3 show the quarterly number of pages of advertisements in Byte magazine devoted to hardware, software, and peripherals (respectively) using different competing platforms. We chose Byte because unlike other computer magazines, Byte is a general magazine that covered developments for all operating systems. Some software was compatible with several platforms and was advertised in that manner. In such a case, each platform receives an equal proportion of the advertisement.

Recall that the $U_i's$ represent the availability of software and peripherals, not actual sales. We believe that the amount of software and peripheral advertising data is a natural proxy for the relative number of complementary products available for a particular operating system. Since the advertisements in Byte magazine during the relevant period were for particular software products and peripherals rather than advertisements for mail order software

[7] See Gabel [1991], Bresnahan and Greenstein [1992], and Langlois and Robertson [1992].

[8] There is a literature that argues that IBM/DOS succeeded, in part, due to the openness of its architecture as compared to Apple's. In contrast, we want to focus on the factors that determined the success and failure of the two fully open platforms, an issue that has largely escaped analysis. Hence, our analysis focuses on the role stochastic, network-related, events had on adoption decisions and platform competition between the two fully open platforms.

companies, we believe that the data are a good proxy for availability of complementary products.[9]

We use the hardware advertising data as a proxy for the sales of the various operating systems. We employ hardware advertising data rather hardware sales data in order to be consistent with the software/peripheral data and because it is extremely difficult to obtain detailed sales information, which is consistent over time, about all suppliers and products for each platform.

This data has strengths and weakness for our purpose. Its main strength is that it provides a quantitative and consistent indication of the growth, commercial success, and failure of all the categories of components associated with these different computing platforms. Because it is so difficult to construct consistent measurement of new or incipient markets, this may be the only measure that can do so. However, there is no generally accepted theory of advertising for high-technology markets, nor any systematic empirical literature on the topic.[10] So there is no commonly accepted way of relating advertising to the rate of sales, or the installed base. We are convinced, however, that the observed level of these ads positively correlates with real economic activity. We are especially confident of this conclusion when we examine aggregate statistics, which averages out many potential small errors at individual companies. First, we are confident that as the total sales for a type of product increases, so too do the total level of advertising. Second, the lags between advertising and real economic activity do not appear to be long – e.g., conventional wisdom places this industry among the fastest in its responsive to market signals and new sales trends. Third, we are also convinced that advertising is segmented across different sub-component markets, so we can differentiate between different types of advertising for different components in a sensible way. Therefore,

[9]Of course, actual sales of software would also probably be a good proxy for the availability of complementary products.

[10]Despite economists' general interest in the phenomena of advertising, as a research topic in itself, there is almost no precedent for using this type of data to learn about features of the underlying high technology market. We are aware of only one other attempt to examine advertising in high- technology markets. Klenow, 1994, uses news releases and announcements to track the entry of new goods.

we posit that the total advertising for a category of components positively correlates with the growth and commercial success or failure of the category of components in this market. The total of commercial advertising for a component category reflects the underlying adoption behavior of users and equilibrium outcomes of inter-platform competition. This is surely right in the long run, since vendors in this market responded to successful sales with more advertising and to commercial failure with less (or none). The main reason for expecting difficulty for our purposes is that some advertising has speculative and signalling motives in the short run, as new products are rolled out. These problems suggests that we should take great care below not to overstep our interpretation.

Several vendors sold machines to customers between 1975 and 1980. The vast majority of these early users tended to be, and perhaps needed to be, computer literate, and likely included many tinkerers and hobbyists. These are the techies in our model. The benefits derived by the early users from their microcomputers were to a much greater extent a function of the user's ability to experiment and do much of programming, as compared to later users - who are the non-techies of the model.

From the figures, it is obvious that CP/M was the dominant operating system. One reason for the success of CP/M was relative abundance of available application software, which was available for free within the hobbyist community. Since the standalone system values were relatively low, the market was (as predicted by Proposition 2) limited to techies.

A dramatic change in the market for operating systems occurred in the early 1980s shortly after the introduction of the IBM PC in 1981. The IBM personal computer primarily used the MS-DOS operating system.[11]

As Langlois and Robertson [1992] document, the change in platforms underwent two phases. One occurred within the 1981-1982 period, when CP/M and DOS operating systems competed and the outcome was uncertain. Indeed, the July 1982 edition of Byte magazine devoted 26 pages to an analysis of the two 16 bit operating systems (the CP/M-86 and

[11] The IBM PC also could run the CP/M operating system.

MS-DOS) competing for dominance. During this phase, there was not yet sufficient appeal for non-techies to enter the market, despite the competition between the two platforms.

There is evidence that during this phase, CP/M, the early leader, was viewed as the ex ante superior system, at least concerning expectations about the number of complementary software products that were likely to be available in the immediate future. In the detailed comparison of the CP/M-86 and the MS-DOS operating systems that appeared in Byte magazine in 1982, Richard Lomas, a system manufacturer wrote, “In seeking languages and applications, I have found more available for CP/M-86 than MS-DOS."[12] More importantly, there were expectations that CP/M would retain this relative edge over time. Lomas noted that the CP/M software was also compatible with MP/M-86, a multi user system. The upward compatibility of MS-DOS software to Xenix (the multi user system specified by Microsoft) was less certain. Lomas remarked that “most if not all software running under MS-DOS will not run under Xenix."

Thus, many of the techies adopted CP/M systems in the 1981-1982 period. Figure 2 shows that as late as 1983, software vendors using CP/M invested almost as heavily in advertising as those using MS-DOS.

On the other hand, MS-DOS was viewed by many as the ex post superior system, that is, if the applications software for MS-DOS did materialize, there was general agreement that MS-DOS was “a better and faster single-user single-tasking operating system for nontechnical users."[13] In terms of the model, many believed that that the U_i for MS-DOS was larger than the U_i for CP/M.

One reason for this assessment was that IBM had tremendous existing customer base in traditional data processing shops throughout large corporations. Its existing marketing and support network initially viewed the PC as a complement to already established mainframe networks, where most users had experience with terminals. PCs could act as intelligent

[12]Note that this edge in application programs corresponds with figure 2.
[13]BYTE Magazine, July 1982, p 331.

terminals, and with a bit of technical gerrymandering at first, and less so as IBM improved the system software, could transfer data from mainframes to small applications on the PC. When user-friendly spreadsheets, databases and wordprocessors appeared on DOS, these PCs were able to perform simple analytical and word-processing tasks while by-passing capacity constraints associated with the use of a central data base on a mainframe. The Techie-oriented systems that preceded the IBM PC were less able to address both sets of needs. In sum, the initial IBM PC initially represented a promise of increased functionality to a large class of new PC users: existing mainframe users.[14]

The installed base of mainframe users perhaps also provided greater assurances of a market for software, and provided software developers incentives to develop software for DOS-based systems. Other factors also affected the outcome. In contrast to the early Apple line of microcomputers, the IBM PC with its MS-DOS operating system was an open architecture system. Gabel [1991] provides evidence that software applications for the proprietary Apple operating system declined significantly with the advent of the IBM PC. Of course, CP/M was also an open system.[15] Indeed both DOS and CP/M operating systems could be run on the early Intel 8086 chips.[16]

Nevertheless, by 1984, Gabel [1991] notes that there were 11,000 different software programs available for the MS-DOS operating system. By the 1984-1985 period (Langlois and Robertson's second phase), the IBM PC with its MS-DOS operating system had supplanted the CP/M machines. Figures 1-3 show that CP/M hardware and peripheral advertisements ceased to exist and software advertisements had declined significantly.

Thus, a snap shot of the industry in 1985 hardly resembled a snap shot of the industry in 1981. The primary users were technically sophisticated in 1981. They were general purpose

[14] This alone, of course, cannot explain the IBM PC's success. Even as late as 1983, there was widespread dissatisfaction among Data Processing managers with functionality of personal computers in business environment (Friedman and Cornford [1989]).

[15] Openness eventually became associated with cloning. Yet, the significant clone occurred in 1985-87, after the dominance of the standard was established.

[16] See the Lomas article in *Byte* 1982.

by 1985. The main applications were limited in 1981 and often were not user friendly. In 1985 applications were varied and many emphasized their “ease-of-use". And most interesting for our purposes, the dominant technical standards embedded in the operating systems of the majority of PCs in 1981 differed from those embedded in the majority of PCs in 1985. Since most of the new application software was incompatible with the CP/M systems, a large fraction of the users of PCs in 1981 found themselves orphaned by 1985. Figure 4 summarizes these “snapshots."

In the next Section, we examine the advertising data to look for differences in the combinations of software, hardware and peripherals sold to early users and late users. Based on these historical facts and the theoretical model, we expect that the later (general purpose) users would be more reluctant than early (technical) users to purchase systems without the availability of a significant amount of complementary software.

8 Econometric Evidence

The empirical analysis investigates the early PC computing market. Our theoretical model suggests that where orphaning occurs, the early adopters and the later adopters would have qualitatively different characteristics. In particular, early adopters would be less reliant on software than later adopters. Hence, we expect a different pattern of sales for hardware and software (and peripherals) between CP/M in the early years in which it was more dominant and MS-DOS in the later years in which it was dominant. More precisely, for MS-DOS, we expect that previous sales of applications software will be a better predictor of future hardware and software sales than previous hardware sales.

We track the history of components associated with DOS and CP/M, the two dominant “open" platforms. Both were “open" in the sense that their operating system specifications were known to potential third-party vendors of software and peripheral hardware. For each platform, we collected advertising data for the following three categories: hardware, software and peripherals. For reasons explained below, we focus on describing and interpreting the relationship between contemporaneous and lagged commercial activity associated with hardware and software. First we discuss characteristics of the data and then perform our analysis.

We track the CP/M market from April 1978 to October 1986, which is almost the entire lifetime of products associated with the platform. We track the DOS platform from July 1981, the date any product on the DOS platform was first advertised, to October 1986. We stop at this point primarily because the advertising associated with products using the CP/M platform is so scattered and rare as to no longer warrant much interest.[17]

We collect quarterly observations, which results in 35 and 22 complete observations for CP/M and DOS respectively. Table 1 presents some basic summary statistics and the figures display histories. As shown in the figures, advertising for the DOS platform grows over the entire period, while advertising for the CP/M platform peaks around 1982-3. Total advertising grows over the whole period, reflecting the entry of many new consumers into this market. The growth and death of total advertising conforms closely to industry perceptions about the growth and death of these platforms, which we take as further assurance that total advertising tracks commercial activity.

It is insightful to compare that the relative amounts of software and peripheral advertising with that for hardware. The summary statistics in Table 1 show that the two platforms have very different patterns. MS-DOS has a much higher proportion of software and peripheral advertising relative to hardware advertising. This most certainly reflects a real economic phenomenon.[18] We interpret this pattern additional evidence that these data are good proxies

[17]While there was advertising for other proprietary platforms in this period, notably Apple, TRS, and Atari, these are less interesting. First, they are quantitatively less important. Second, the platforms are not consistently open, so our theoretical framework has less to say about their characteristics. Third, our impression is that these platforms were almost exclusively aimed at the market for games and, ultimately, a different set of consumers.

[18]Indeed the life-cycle of the CP/M platform suggests that the CP/M ratios of software/hardware and peripherals/hardware were biased upwards. Near the time of CP/M's death there was almost no hardware advertising while there was still plenty of software and peripheral advertising.

for sales.

To further examine if there are dynamic differences in these variables for the two operating systems, we use regression analysis to summarize the history of DOS and CP/M. Tables 2 and 3 present OLS regression results from regressions of hardware on software and peripherals and visa-versa.[19] We include only one lag. A second lag does not markedly change the coefficients on the first lag.[20]

Because our theoretical framework provides no natural specification for the different effects of software and peripherals, we also show three alternative non-tested specifications of the non-hardware variables. In model 1 we use all three variables. In model 2 we use only hardware and software. In model 3 we add peripherals to software. Most specifications fit well, even though we never use more than three explanatory variables. Therefore, we conclude that these specifications provide a reasonable and concise description of the market's change over time.

First we examine the question: what is the relationship between lagged values and contemporaneous values of hardware and software? In the case of CP/M, lagged software and peripherals significantly predicts later hardware advertising, controlling for lagged hardware. For example, an extra page of page of software advertising precedes one-third of a page of hardware advertising. Similarly, lagged hardware significantly predicts software in most specifications, though the same is not necessarily so for peripherals. For example, an extra page of page of hardware advertising precedes almost half a page of software advertising. We conclude that there is a statistically robust and economically important interaction between lagged commercial activity and contemporaneous activity across hardware and software components in the CP/M platform.

We observe a different relationship in the case of DOS. First, lagged software does significantly predict hardware advertising in all of our specifications. For example, an extra page of

[19]The numbers in parentheses in tables 2 and 3 are the standard errors. A “*" means that the t-stat exceeds 1.64, while “**" means that the t-stat exceeds 1.96.

[20]For many specifications, we cannot reject the hypothesis that all second lags are jointly zero.

software advertising precedes one-half of a page of hardware advertising. However, lagged hardware does not significantly predict software advertising in any of our specifications. Nor does peripheral advertising predict hardware or software advertising. We conclude that there is an economically important relationship between lagged commercial activity in DOS software and later DOS hardware. However, the relationship is unidirectional: lagged hardware does not predict software.

Now we can examine the question: are the coefficients describing the commercial activity for DOS the same as those describing CP/M? The answer is clearly no. On a specification by specification comparison, the two regression results are not similar. Coefficients take on different signs, magnitudes, and significance. Coefficients describing the relationship between contemporaneous and lagged values differ. The patterns associated with DOS advertising contrasts sharply with those associated with CP/M. Our interpretation is that the success of DOS depended largely on the availability of software. CP/M displays patterns reflecting its appeal primarily to early adopters.

Category	*Mean*	*Std.Dev.*	*Minimum*	*Maximum*
Hard CPM	7.28	6.43	0.00	20.00
Soft CPM	11.54	7.74	0.50	27.50
Periph CPM	3.60	2.79	0.00	10.00
Hard DOS	11.75	8.75	0.00	29.50
Soft DOS	25.02	17.56	0.00	62.00
Periph DOS	22.11	11.32	0.00	38.00

Table 1: CPM: April 1978- Oct. 1986; DOS: July 1981 - Oct. 1986

	Model 1			Model 2		Model 3	
Dept. Var.	Hard	Soft	Periph	Hard	Soft	Hard	Soft+Periph
Const	-0.87 (0.74)	1.7* (0.88)	0.35 (0.50)	-0.69 (0.77)	1.6* (3.6)	-0.89 (0.74)	2.2* (1.2)
Lag Hard	0.39** (0.14)	0.45** (0.17)	0.04 (0.10)	0.43** (0.15)	0.44** (0.17)	0.38** (0.14)	0.58** (0.23)
Lag Soft	0.32** (0.13)	0.60** (0.15)	0.27** (0.09)	0.41** (0.12)	0.58** (0.29)		
Lag Periph	0.45* (0.25)	-0.12 (0.29)	-0.06 (0.17)				
Lag Soft+Periph						0.35** (0.09)	0.56** (0.14)
R-squared	0.86	0.86	0.65	0.84	0.86	0.86	0.85

Table 2: CPM: April 1978- Oct. 1986

	Model 1			Model 2		Model 3	
Dept. Var.	Hard	Soft	Periph	Hard	Soft	Hard	Soft+Periph
Const	0.87 (1.45)	1.3* (3.25)	4.73** (1.98)	1.61 (1.18)	4.4 (2.7)	-0.57 (1.44)	6.9* (3.5)
Lag Hard	-0.25 (0.18)	0.09 (0.41)	-0.34 (0.25)	-0.18 (0.16)	0.40 (0.38)	-0.29 (0.20)	-0.23 (0.49)
Lag Soft	0.49** (0.08)	0.58** (0.18)	0.29** (0.11)	0.51** (0.07)	0.70** (0.18)		
Lag Periph	0.10 (0.12)	0.44 (0.27)	0.69** (0.16)				
Lag Soft+Periph						0.35** (0.06)	0.97** (0.14)
R-squared	0.86	0.82	0.84	0.85	0.80	0.82	0.89

Table 3: IBM: July 1981 - Oct. 1986

9 Conclusion

In this paper we addressed the interdependent decision problems facing buyers in choosing which of the early microcomputers to purchase and when to make the purchase, and the corresponding dynamic pricing problem for suppliers of those microcomputers. We find conditions under which price competition among vendors induces consumers to buy early, despite the uncertainty about the development of complementary software.

We also find conditions under which some consumers adopt early whereas others wait for uncertainty to be resolved; when these conditions are satisfied, it is possible that late adopters purchase a different system than the early adopters, leaving the latter stuck with an “orphan" technology. Our model suggests that orphaning will occur only when more and better software than expected becomes available for a technology in competition with that of the early leader. Since the amount and variety of complementary software cannot be predicted with certainty, early adopters face some inherent risks, and orphaning can occur.

An empirical implication of our theoretical analysis is that when orphaning occurs, software is more likely to precede hardware for the technology of the “late" leader than for the technology of the “early" leader. The data we present support this prediction; there is evidence from the early microcomputer market that the pattern of adoptions and orphaning was associated with the later adopters waiting for software and other complementary products to develop. In particular, the advertising patterns associated with the DOS platform differ from those associated with CP/M, the leading operating system among early microcomputers. In contrast to CP/M, there is evidence that the success of DOS depended largely on the entry of many DOS-based software vendors and the associated increase in the availability of DOS compatible complementary software.

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Appendix: Low Basic System Valuations:

Here we assume that marginal costs are constant over time. However, we suppose that "non-techies" preferences are such that $c - U_b < \theta^N < c < \theta^T$, where, as before, c is the unit production cost which is both constant over time and with the level of output.

The first two inequalities mean that "non-techies" have no interest in a system without supporting services at any price that covers marginal production costs, but would be willing to pay a premium for either system if software were available. Three outcomes are possible:

(1) All consumers purchase the ex ante superior system in the first period, (2) Techies purchase the ex ante superior system in the first period and Non-techies make purchases in the second period, and (3)Techies purchase the ex ante superior system in the first period and Non-techies do not make any purchases in the second period.

Outcome (2) occurs if at least one of the systems experiences innovation, while outcome (3) occurs if neither system experiences innovation.[21] Under both outcomes (2) and (3), techies can get stuck with orphan technologies. In particular, techies adopt the ex ante superior system. Non-techies who wait end up purchasing a system that has experienced innovation. Hence the groups may purchase different systems.

The intuition for this result is to similar to the case of falling marginal costs. The only qualitative difference between the cases is that in this non-techies will not make any purchases in this case if they do not purchase in the initial period and neither system experiences innovation.

We now provide the formal result. In advance of the proposition, let

$$\tilde{\theta} = \frac{c(1-\rho_a\rho_b) + U_b\rho_b(\rho_a - 1)}{2-\rho_a\rho_b},$$

$$\hat{\theta} = \frac{N^T c(1-\rho_a\rho_b) + N^N c(1-\rho_a) - N^T\rho_b U_b(1-\rho_a)}{N^T(2-\rho_a\rho_b) + N^N(2-\rho_a)},$$

$$\grave{\theta} = \frac{c(1-\rho_a\rho_b) - \rho_a(U_a - \rho_b U_b)}{2-\rho_a\rho_b}, \text{ and}$$

$$\bar{\theta} = \frac{N^T c(1-\rho_b\rho_a) + N^N c(1-\rho_b) - N^T\rho_a(U_a - \rho_b U_b)}{(2-\rho_a\rho_b)N^T + N^N(2-\rho_a)}.$$

Proposition 4 *(I) First Suppose that the ex ante superior system, A, is also ex post superior system, that is* $\Gamma = \rho_b U_b - \rho_a U_a < 0$.

(I) Then there is a unique equilibrium in which:

[21] Outcome (3) will also occur in the uninteresting case in which $\theta^N < c - U_b$.

1. *All consumers buy early from the ex ante superior system,A, if* $\theta^N \geq \tilde{\theta}$*. Initial period prices are* $p^0 = (-\Gamma + c, c)$.

2. *For* $\theta^N < min[\hat{\theta}, \tilde{\theta}]$*, techies purchase the system A in the first period. Non-techies make a purchase only in the second period if at least one innovation occurs. The first period prices are* $p^0 = (-\Gamma + c, c)$.

3. *If* $\hat{\theta} < \tilde{\theta}$*, there is a third region: For* $\hat{\theta} < \theta^N < \tilde{\theta}$*, all consumers buy system A in the first period, the first period price for system B is 0 and for system A the first period price is* $p_a^0(\theta^N) = \rho_a(U_a - \rho_b U_b) + \theta^N(2 - \rho_a\rho_b) + \rho_a\rho_b c < -\Gamma + c$.

(II) Now suppose that the ex ante superior system, A, is inferior ex post, that is, $\Gamma > 0$*. Then there is a unique equilibrium in which:*

1. *All consumers buy system A early if* $\theta^N \geq \grave{\theta}$*. Initial period prices are* $p^0 = (c, \Gamma + c)$.

2. *For* $\theta^N < min[\bar{\theta}, \grave{\theta}]$*,techies purchase system A in the first period. Non-techies make a purchase only in the second period if at least one innovation occurs. The first period prices are* $p^0 = (c, \Gamma + c)$.

3. *If* $\bar{\theta} < \grave{\theta}$*, there is a third region: For* $\bar{\theta} < \theta^N < \grave{\theta}$*, all consumers buy system A in the first period, the first period price for system B is 0 and for system A, the first period price is* $p_a^0(\theta^N) = \rho_b U_b(1 - \rho_a) + \theta^N(2 - \rho_a\rho_b) + \rho_a\rho_b c < \Gamma + c$.

The intuition behind this result is essentially the same as Proposition (2). The Techies buy early. The price that the Techies pay, will, if the innovation is not so great, or its probability sufficiently low, and the stand-alone value for the Non-Techies is high enough, also induce the Non-techies to buy early. The main difference between Proposition 2 and Proposition 4 is the possibility of a third region in which the initial price depends on Non-techies stand-alone values. In this case, the firm with the ex ante superior system would prefer to sell to both the Techies and the Non-techies in the initial period than to sell only to the Techies in the initial period, and to the Non-techies in the later period if has the better system ex post. The critical values of the stand-alone values depend on the relative number of Techies and Non-techies. Before we prove Proposition (4), we state and prove the following lemma.

Lemma 2 *Suppose that* $\theta^N + U_b > c$*. Further suppose that techies purchase in the initial period and that non-techies do not. Then there is a unique equilibrium in the final period, with the following prices:*
(i) If $\alpha = (1, 1)$ *then* $p_a^1 = U_a - U_b + c$ *and* $p_b^1 = c$*. (ii) If* $\alpha = (1, 0)$*, then* $p_a^1 = U_a + \theta^N$ *and* $p_b^1 = c$*.*
(iii) If $\alpha = (0, 1)$*, then* $p_b^1 = U_b + \theta^N$ *and* $p_a^1 = c$*.*
(iv) If $\alpha = (0, 0)$ *then* $p_a^1 = p_b^2 = c$*.*
If non-techies wait, they receive an expected utility of

$$\rho_a \rho_b (U_b + \theta^N - c). \tag{4}$$

Proof: The lemma follows immediately from Lemma 1, with the modification that when a single firm innovates, the maximum price it can charge non-techies in the second period is $U_i + \theta^N < U_i$ + c, since $\theta^N < c$. ■

Proof of Proposition (4).

We first prove the result for case when the ex ante superior system is also superior ex post, that is, for $\Gamma = \rho_b U_b - \rho_a U_a < 0$ and $U_a \geq U_b$. Suppose that the techies buy the ex ante superior system in the first period. We will show later that this will be true in equilibrium.

Suppose the initial period price for system a is $p_a^0 = -\Gamma + c$, and the initial period price for system b is $p_b^0 = c$. Note that if all consumers buy early, the fact that there is price competition and the difference in expected values of the two systems is Γ implies that these would have to be the first period equilibrium prices. If firm a were to raise its price, firm b, which otherwise would not make any sales, could then charge a positive price and earn profits.

Given these prices and first period prices as described in Lemma 2, the expected utility of non-techies from buying early is

$$\rho_a U_a + 2\theta^N - (-\Gamma + c) = \rho_b U_b + 2\theta^N - c. \tag{5}$$

If the non-techies wait, from Lemma 2, they receive an expected utility of $\rho_a \rho_b (U_b + \theta^N - c)$.

Comparing (5) and (4), buying early dominates buying late for non-techies at prices $-\Gamma + c, c$ whenever

$$\theta^N \geq \frac{c(1-\rho_a\rho_b) - U_b\rho_b(1-\rho_a)}{2-\rho_a\rho_b} \equiv \tilde{\theta} \tag{6}$$

Note that $\tilde{\theta} < c$. So for $\theta^N > \tilde{\theta}$, all consumers (techies and non-techies) alike purchase system a, the ex ante superior system, in the first period.

Now consider the case $\theta^N < \tilde{\theta}$. If firm "a" wants to sell to both types in the first period, then it must set p_a^0 low enough to attract non-techies. From (4) such a price, $p_a(\theta)$ must satisfy

$$\rho_a\rho_b(U_b + \theta^N - c) \leq \rho_a U_a + 2\theta^N - p_a^0$$

Let

$$p_a^0(\theta^N) = \rho_a(U_a - \rho_b U_b) + \theta^N(2-\rho_a\rho_b) + \rho_a\rho_b c \tag{7}$$

When $\tilde{\theta} > \theta^N$, the profits from selling to all consumers in the first period are $N[p_a^0(\theta^N) - c]$ and the expected profits from selling only to the techies in the first period are

$$-N^T\Gamma + N^N[\rho_a(1-\rho_b)(U_a+\theta^N) + \rho_a\rho_b(U_a - U_b + c) - \rho_a c],$$

where the second term represents the expected profits from selling to non-techies in the second period. The profits to selling to both types are larger whenever

$$\theta^N \geq \hat{\theta} = \frac{N^T c(1-\rho_a\rho_b) + N^N c(1-\rho_a) - N^T\rho_b U_b(1-\rho_a)}{N^T(2-\rho_a\rho_b) + N^N(2-\rho_a)}. \tag{8}$$

It can easily be verified that $\hat{\theta} < c$.

When $\hat{\theta} \geq \tilde{\theta}$, (i) for $\theta^N \geq \tilde{\theta}$, both types purchase the ex ante superior system in the first period at a price of $|\Gamma|$, (ii) for $\theta < \tilde{\theta}$, only the techies purchase the ex ante superior system in the first period (also at a price of $|\Gamma| + c$.) Non-techies make no first period purchases.

When $\hat{\theta} < \tilde{\theta}$, there are three regions: (i) for $\theta^N \geq \tilde{\theta}$, both type of consumers purchase system "a", the ex ante superior system in the first period at the price of $|\Gamma| + c$, (ii) for $\hat{\theta} \leq \theta^N < \tilde{\theta}$ both types purchase system "a" in the first period, but at a price of $p_a^0(\theta^N)$, (iii) if $\theta^N < \hat{\theta}$, only techies purchase the ex ante superior system at the price $|\Gamma| + c$ in the first period.

Thus, assuming all techies purchase the ex ante superior system in the first period we have shown the result for the case in which $\rho_a U_a \geq \rho_b U_b$ and $U_a \geq U_b$. We now show that in fact techies will buy the ex ante superior system in the first period

There are three potential cases: (i) $\theta^N \geq \tilde{\theta}$, (ii) $\tilde{\theta} > \theta^N \geq \hat{\theta}$, and (iii) $\theta^N < \hat{\theta}$. In case (i) all consumers purchase system "a" in the initial period. The prices are $p_a = -\Gamma + c$ and $p_b = c$.

In case (i), "non-techies" are purchasing in the initial period, so Proposition 1 shows that techies will also purchase rather than wait.

In case (ii), "non-techies" wait in equilibrium. Thus, regardless of whether techies wait or purchase in the initial period, equilibrium final period prices are given by Lemma 2. Given these prices the expected utility of waiting for techies is less than $\theta^T + \rho_a \rho_b U_b$. The expected utility of purchasing in the initial period is at least as large as $2\theta^T + \rho_b U_b - c$, which is greater than the expected utility of waiting, since $\theta^T > c$.

Finally, in case (iii) the initial and final period prices are the same as in case (i), and so techies will have incentives to buy the ex ante superior system in the initial period in this case too.

We now prove the result for the case that the ex-ante superior and ex-post superior systems are different, that is, $\rho_a U_a < \rho_b U_b$. The proof is constructed in a similar manner. We now derive $\grave{\theta}$ and $\bar{\theta}$, which are analogous to $\tilde{\theta}$ and $\hat{\theta}$ respectively.

Suppose the first period price for the ex ante superior system, system "b", is $\Gamma = \rho_b U_b - \rho_a U_a + c$, and the price for the other system is c. Then non-techies who purchase system "b" early will derive expected utility of $\rho_b U_b + 2\theta^N - \Gamma - c = \rho_a U_a + 2\theta^N - c$.

Recall that the non-techies will derive an expected utility from waiting of $\rho_a \rho_b (U_b + \theta^N - c)$. Comparing these two expressions, non-techies will buy system a early whenever

$$\theta^N \geq \frac{c(1 - \rho_a \rho_b) - \rho_a (U_a - \rho_b U_b)}{2 - \rho_a \rho_b} \equiv \grave{\theta}. \tag{9}$$

For $\theta^N < \grave{\theta}$ firm A can sell to both types in the initial period when the price it charges, p_b^0, satisfies

$$\rho_a \rho_b [U_b + \theta^N - c] \leq \rho_b U_b + 2\theta^N) - p_b^0.$$

The most firm "b" can charge and still sell to both types in the initial period is denoted $p_b^0(\theta^N)$ and equals

$$p_b^0(\theta^N) = \rho_b U_b (1 - \rho_a) + \theta^N (2 - \rho_a \rho_b) + \rho_a \rho_b c. \tag{10}$$

By selling to both techies and non-techies, firm "b" will get profits of $N p_b^0(\theta^N)$. Firm A can set its first period price at Γ, sell only to techies in the first period, and earn expected profits of $N^T \Gamma + N^N \rho_b (1 - \rho_a)(U_b + \theta^N - c)$, where the first term is the first period profits from selling to the techies and the second term is the expected profits from selling to non-techies in the second period. Selling to techies is more profitable than selling to both types in the first period whenever $\theta^N < \bar{\theta}$.

The result then follows by showing that, analogous to the case in which system "a" is both ex ante and ex post superior, techies always purchase in the initial period. ■