

Pricing and Timing of New Products in the Presence of an Installed Base

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Abstract

This paper studies a vendor's timing and pricing of a new product in the presence of an installed base. Using a stylized model with overlapping generations of a durable product and heterogeneous consumers, we show that the valuation of former patrons toward the new product is dynamic over time. Together with new customers who do not own the old product, such dynamic valuation leads to a demand structure that is more heterogeneous than those studied in the prior literature. We found that the vendor would often prefer intertemporal but not static price discrimination in maximizing its profits. Surprisingly, such intertemporal price discrimination is sometimes perfect in the sense that the vendor may capture all surplus from consumers. We also show that the vendor would at times delay selling the new product so as to overcome the negative influences caused by time inconsistency and cannibalization. Overall, we found that the vendor's equilibrium choices often result in socially inefficient outcomes, and upgrade pricing may not rectify such inefficiencies. In fact, the vendor may even forgo using upgrade pricing in equilibrium. Hence, direct price discrimination based on purchase history may lose its merit when a vendor dynamically prices a new product in view of an installed base of old products.

Key words: Installed base, upgrade, price discrimination, delayed product introduction

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1. Introduction

In many durable goods markets firms face consumers with different purchase histories. The different purchase histories may arise because people exhibit different valuations toward the products, and so they may not buy the products at the same time. Firms are often happy to sell products only to those people who value the products highly, because they may capture higher profits from such people than selling the products to all consumers at lower prices (Mussa and Rosen 1978; Stokey 1979; Moorthy 1984).

However, the firms' decisions would become more complicated if new generations of durable products arrive at the market. Suppose a durable good vendor faces a population of consumers who variously own / do not own a current-generation product. A new generation with better quality has arrived, and the vendor can sell it to consumers without incurring significant costs. When should the vendor sell the new product to consumers? Should it target at people who own the old product, or new customers? Should the vendor continue to sell the old product? How should it set the prices?

The answers to these questions are not trivial because the vendor faces a significant cannibalization and time inconsistency problem. As previous studies had characterized (e.g., Dhebar 1994; 1996; Fishman and Rob 2000), the existing installed base of the old product reduces some consumers' need for the new product (a forward cannibalization effect). At the same time, consumer anticipation of the new product makes continue selling the old product difficult for the vendor (a backward cannibalization effect). In fact, consumers may "balk" if new generations of products are launched too rapidly (Dhebar 1996).

The previous studies have not considered the situation when the installed base is not complete in the sense that not all consumers own the old product (cf. Bayus 1992; Fishman and Rob 2000), and when the vendor can sell the new product at different time (cf. only in one specific period; e.g., Fudenberg and Tirole 1998; Lee and Lee 1998). The incomplete

installed base facilitates selling both products in the market, and, compared with the case with full installed base, the vendor may face fewer balking consumers. The option to sell the new product at different time periods makes intertemporal price discrimination feasible, but it re-introduces time inconsistency. The interaction of these two features gives rise to decision complexities that have not been not well explored in the prior literature.

In this study, we analyze the vendor's timing and pricing decisions when it faces an installed base of the old product. Our setting allows the vendor to decide whether, when, and how much to sell both the old and new products, and so it is more general than past studies which *ex ante* fixed the product sequences (e.g., Moorthy and Png 1992; Dhebar 1994; Kornish 2001) or the time of introducing / selling new products (e.g., Waldman 1993; 1996a; Fudenberg and Tirole 1998; Lee and Lee 1998).

In particular, our model could accommodate two types of demand dynamics: first, former patrons (people who own the old product) exhibit an increasing willingness to buy the new product due to depreciation of the (old) product in hand. Second, the service provided by the old stocks tends to make buying the new product less imminent for former patrons. Together with people who do not own the old product (i.e., potential new customers), the vendor faces an aggregate demand structure that is highly dynamic and heterogeneous. Our equilibrium analysis shows that the vendor could use a variety of strategies, some of which being rather innovative, to respond to such a demand structure.

Our key findings are as follows. First, we found that in most cases the vendor would not immediately sell the new product only to high valuation consumers who already own the old product. So, for some multi-generation products that have not completely penetrated the market, the early buyers of new products may not always be the people who place the highest valuations on the products. We also found that it is difficult for the vendor to practice static price discrimination by selling the entire product line to different consumer segments at the

same time (cf. Moorthy and Png 1992). So, even without costs, durable goods vendors may sometimes not want to maintain all product vintages in a single period.

Second, we found a new equilibrium strategy which enables the vendor to extract all consumer surplus using (perfect) intertemporal price discrimination. With this strategy, the vendor does not need to explicitly identify consumers. It would sell the new product to low valuation consumers followed by high valuation consumers. The price of the new product would increase over time, but consumers would self-select into the prices designed for them. Our analysis provides a new perspective on why some vendors would paradoxically increase the prices of their new products over time (cf. Bayus 1992).

Third, we found that the vendor would often delay selling the new product even when marginal cost is zero. Contrary to existing literature, however, the motivation for such delays is not to soothe balking consumers or to accumulate future demand for the new product (e.g., Dhebar 1994; 1996). Rather, they arise mostly because of time inconsistency. Our research formally establishes “delayed introduction” as one strategy to address the time inconsistency problem (cf. Fishman and Rob 2000; see also, Waldman 2003).

Finally, we show that time inconsistency and cannibalization within the product line often cause the vendor to select equilibrium strategies that are socially inefficient. Further, the inefficiency applies to all consumers (cf. only low valuation consumers, as in Mussa and Rosen 1978; Moorthy 1984; and Moorthy and Png 1992). Upgrade pricing could sometimes rectify the problem and restore social efficiency. However, we found the striking result that the vendor would at times forgo upgrade and instead use intertemporal price discrimination in equilibrium. So, an upgrade policy is not a simple panacea to restore social efficiency, or to maximize the vendor’s profits (cf. Lee and Lee 1998; Fishman and Rob 2000).

Our theory applies to general business settings that involve decision making in view of an installed base of old products. Examples include changes in internal management (new

management inheriting an installed base of old products from predecessors), mergers and acquisitions (acquirer inheriting an installed base from acquirees), and the exit of prominent competitors in a concentrated market (incumbent vendor facing an installed base created by the exited competitors). The common features in these examples are that the vendors face an (exogenously formed) installed base of old products, and that the vendors have to make long term planning for all of their current / future products.¹

In particular, our theory may potentially shed some lights on why Sony's PlayStation 3 generated limited sales (in view of the more than 100 million units of PlayStation 2 that had been purchased by consumers), why Apple's iPhone 3G was launched latter than iPhone 2G (perhaps to penetrate market segments who were contented with 2G cellular services), why the various generations of Apple iPod had little overlap in time (perhaps because static price discrimination using multiple product vintages was less profitable than a complete product replacement strategy), and why some automobile manufacturers launched new car models by offering discounts to early buyers (perhaps to exercise the type of perfect intertemporal price discrimination that we characterize in this study).

Similarly, our findings could inform policy makers in facilitating efficient operations of markets with installed bases of old products. The policy makers should assess the social implications of different product line and pricing strategies given that such strategies may interact with the existing installed bases, and evaluate if explicit measures, such as promoting product upgrades or replacements, could help regulate the pace of product consumption.

The rest of this paper is organized as follows. Section 2 reviews the related literature. Section 3 presents the structure and assumptions of our research model. Section 4 reports the analyses and characterizes the equilibria. Finally, Section 5 concludes the paper.

¹ For example, when Lenovo acquired the personal computer division of IBM, it had to set future product line and pricing strategies by taking into account owners of existing IBM personal computers. After the OS/2 was withdrawn from the operating systems market in 2006, Microsoft faced a sizable pool of potential customers who had been using the OS/2 in their computer systems, and who in due course may switch or upgrade to future versions of the Windows operating system.

2. Prior Literature

This research is grounded on the extensive literature in durable goods monopoly and pricing. Two streams of work are particularly relevant. The first is on market segmentation and price discrimination (e.g., Mussa and Rosen 1978; Stokey 1979; Moorthy 1984; Moorthy and Png 1992). The other is on planned obsolescence and product replacement strategies (e.g., Coase 1972; Bulow 1982; 1986; Waldman 1993; 1996a; 1996b).

Research on market segmentation and price discrimination has demonstrated that if a monopolist is unable to identify consumers with heterogeneous valuations for quality, it may induce consumer self-selection by offering a menu of qualities, i.e., static price discrimination (Mussa and Rosen 1978; Moorthy 1984), or a sequence of prices for the same product over time, i.e., intertemporal price discrimination (Stokey 1979). By integrating these two types of price discrimination, Moorthy and Png (1992) show that a monopolist vendor often would not sequentially sell a high quality product and then a low quality product to consumers unless cannibalization is significant, consumers are more impatient than the vendor, and the vendor is able to commit to its strategy. Instead, it may prefer to immediately sell the entire product line to consumers. Moorthy and Png's setting does not allow consumers to buy both products over time (so they ruled out upgrade), and it exogenously fixes the product sequence. Hence, their model imposes a stronger structure than the one presented here.

Along a similar vein, Dhebar (1994) and Kornish (2001) study how consumers react to multiple generations of the same durable product. Their research suggests that in some cases the vendor would be better off postponing selling future generations of products, but they did not explicitly characterize such market equilibria. Dhebar's and Kornish's models assume complete product replacement, viz., the vendor could only sell an old product in the first period and a new product in the second period. Hence, their models could not account for static price discrimination and dynamic pricing of new products.

Separately, research on planned obsolescence has focused on a vendor's incentive to introduce a new product which causes economic or physical obsolescence of old products. The researchers typically assume that a new product would render an old product obsolete, but there exists a (often frictionless) second hand market which allows former patrons to sell their old stocks to other low valuation consumers (Bulow 1986; Levinthal and Purohit 1989; Waldman 1996a; 1996b). Their interests mostly lie in how quality improvement and product substitutability affect the vendor's strategies. Accordingly, in these studies consumers would not own both the old and new products at the same time. In fact, in most cases they do not incorporate either static or intertemporal price discriminations.

In a model incorporating product obsolescence and price discrimination, Lee and Lee (1998) characterize the time inconsistency problem caused by technological innovations, and they advocate the benefit of upgrade pricing which could help internalize the losses due to economic obsolescence. In a more sophisticated analysis, Fudenberg and Tirole (1998) study a similar problem, but they further compare how information structure affects the vendor's profitability. They find that in general a frictionless second hand market is more profitable for the vendor (cf. no second hand market but with upgrade pricing).

In both Lee and Lee's (1998) and Fudenberg and Tirole's (1998) settings, after the first period, an installed base of old products would form among high valuation consumers, which sets the stage for the analysis that we present in this paper. However, their analyses do not allow for dynamic pricing of the new product, and so they are not able to study the time profile of consumer utilities.

More importantly, their analyses cannot address questions related to the timing of the new product – the vendor can sell the new product only in one period, and so it could practice static price discrimination with either a product line or product replacement strategy, but not

intertemporal price discrimination with respect to the new product. As we shall show below, this is an important restriction which limits the strategic insights of their studies.²

3. The Model

A monopolist vendor is planning to sell a new generation of durable product in two periods, $t = 1, 2$. Before the arrival of this new product, the vendor (or its predecessors) has been selling an old generation, which results in an installed base of the old-generation product at the beginning of Period 1. We index the old- and new-generation products by $i \in \{O, N\}$, and denote their qualities by q_i . We assume that $q_N > q_O$ due to technological innovations. For ease of exposition, we normalize q_N to 1, and hence $0 < q_O < q_N = 1$. q_O then (inversely) measures the extent of quality improvement embodied in the new product.

Both the old (low-quality) and new (high-quality) products are of the same durability, $n \geq 2$ periods.³ We use $\delta = 1/[1 + \text{interest rate}]$, $0 < \delta < 1$, to denote a one-period discount factor, which is common to both the vendor and consumers. The larger δ is, the smaller the discount in future utilities will be. We further assume zero fixed and marginal costs to focus on the strategic choices of the vendor in respond to demand variations.

On the demand side, there are two types of consumers indexed by $j \in \{H, L\}$, who differ in their valuations of product quality, $v_H \geq v_L$. The high type segment has a size of d_H , the low type segment has a size of d_L , and, without loss of generality, $d_H + d_L = 1$. Let $v_L^H = v_H / v_L$ measure consumer heterogeneity in valuations of product quality (Moorthy and Png 1992). That is, larger v_L^H means that consumers are more “heterogeneous”.

² For example, we found that in many cases the vendor would not sell the new product immediately. That the vendor would sell new products as soon as they are available has been a major assumption in many past studies, especially those that do not endogenize R&D efforts, although some researchers have raised doubts on such an assumption (e.g., Fishman and Rob 2000; Kornish 2001).

³ As we shall illustrate below, the vendor and consumers would rationally price the products by their physical lifespan, and so whether n is substantially longer than the planning horizon of two periods is not important.

Each consumer demands at most one unit of either version of the product (they can, however, buy both products sequentially if they get higher utility from doing so; see, e.g., Fudenberg and Tirole 1998; Lee and Lee 1998). Within its lifespan, the product provides a constant stream of service to consumers; once consumers buy it, they enjoy a “rental” value that equals its quality in each period of service until the product is retired. Hence, each type j consumer values a product with quality q_i and durability n at $v_j q_i [1 - \delta^n] / [1 - \delta]$, which is the discounted sum of rental values. There is no second hand market;⁴ as soon as consumers buy a new product, their old products are retired and provide no usage or residual value.

Each period further comprises two stages. In the first stage, the vendor makes product and pricing announcements based on its knowledge of market demand. In the second stage, consumers make purchase decisions, taking into account their valuations of the products and expectations about future products. There is common knowledge on demand, product quality, durability, and technological innovations, and perfect information on the history of moves by the vendor and consumers. We focus on rational expectations equilibria in which consumers form expectations about the vendor’s strategies, and the vendor fulfills such expectations (see, e.g., Stokey 1981; and Besanko and Winston 1990).

Prior to the beginning of Period 1, there is an existing installed base of the old product, the quantity of which is exogenously given. In particular, we study two settings: one with a partly-covered installed base in which only high type consumers have bought the old product, and the other with a fully-covered installed base in which all consumers have bought the old product.⁵ In the case with a partly-covered installed base, we further separate the analysis by whether the vendor can provide an upgrade option to consumers.

⁴ For a thorough analysis of the impact of a second hand market on the monopolist’s strategies, see Waldman (1996a) and Fudenberg and Tirole (1998).

⁵ Intertemporal product line and pricing studies have typically found that consumers with higher valuations would buy a product first. See, for example, Stokey (1979), Besanko and Winston (1990), Moorthy and Png (1992), Waldman (1996b), Fudenberg and Tirole (1998), Lee and Lee (1998), and Nahm (2004).

We denote the price of product i in period t by p_t^i , and the upgrade price of the *new* product by p_t^U . In the setting with a fully-covered installed base, $p_t^U = p_t^N$, as all consumers own the old product and hence share the same purchase history.

4. Analysis

For ease of presenting the subsequent results, we first define several constants:

$$V_1 \equiv \frac{1 - \delta^n}{1 - \delta^n - q_o[1 - \delta^{n-2}]}, V_2 \equiv \frac{1 - \delta^n}{1 - \delta^n - q_o[1 - \delta^{n-1}]}, \text{ and } V_3 \equiv \frac{1 - \delta^n}{1 - \delta^n - q_o}.$$

$V_2 > V_1 > 1$, and $V_3 > V_2 > V_1$ when $q_o \leq 1 - \delta^n$.

4.1 Demand Characteristics

If a consumer j does not own any product before making a purchase, then she can obtain the full utility from a product. Her willingness to pay for product i in Period t ,

$$b_{it}^j = \frac{v_j q_i [1 - \delta^n]}{1 - \delta}. \quad (1)$$

The corresponding discounted utility at Period 1,

$$B_{it}^j = \delta^{t-1} b_{it}^j. \quad (2)$$

Now, suppose the same consumer has bought the old product and has consumed it for one period at the beginning of Period 1. Then, she would value only the *incremental* utility provided by the *new* product. Her willingness to *upgrade* in Period t ,

$$u_{Nt}^j = \frac{v_j [1 - \delta^n]}{1 - \delta} - \frac{v_j q_o [1 - \delta^{n-t}]}{1 - \delta}. \quad (3)$$

The corresponding discounted utility at Period 1,

$$U_{Nt}^j = \delta^{t-1} u_{Nt}^j. \quad (4)$$

The first term on the right hand side of (3) is the value that the consumer obtains from the new product (recall that $q_N = 1$). The second term is the remaining consumption value of the old product given that it has been consumed for t periods.

By (1) to (4), if $q_O = 0$, that is, if the consumer does not own the old product, then $u_{Nt}^j = b_{Nt}^j$ and $U_{Nt}^j = B_{Nt}^j$. In this case, across Periods 1 and 2, $b_{i1}^j = b_{i2}^j$, but $B_{i1}^j > B_{i2}^j$. That is, the consumer always obtains higher utility from an earlier purchase.

Consider what happens if the consumer owns the old product prior to the beginning of Period 1. First, by (3), her willingness to *upgrade* to the new product *increases* over time (i.e., $u_{N1}^j < u_{N2}^j$), because depreciation of the old product raises the incremental benefit that she can obtain from the new product. Second, by (4), $U_{N1}^j > U_{N2}^j$ if and only if $q_O \leq 1 - \delta^n$, and so the consumer obtains higher utility from an earlier upgrade if and only if the extent of quality improvement is high. If the extent of quality improvement is low, her utility from upgrading to the new product again *increases* over time (i.e., $U_{N1}^j \leq U_{N2}^j$).⁶

By (2) and (4), the changes in consumer utility with respect to t ,

$$\frac{\Delta B_{it}^j}{\Delta t} = \frac{B_{i[t+\Delta t]}^j - B_{it}^j}{\Delta t} = \left\{ \frac{\delta^{t-1}[\delta^{\Delta t} - 1]}{\Delta t} \right\} \frac{v_j q_i [1 - \delta^n]}{1 - \delta} < 0, \quad (5)$$

$$\frac{\Delta U_{Nt}^j}{\Delta t} = \frac{U_{N[t+\Delta t]}^j - U_{Nt}^j}{\Delta t} = \left\{ \frac{\delta^{t-1}[\delta^{\Delta t} - 1]}{\Delta t} \right\} \frac{v_j [1 - \delta^n - q_O]}{1 - \delta}. \quad (6)$$

Denote $\Delta U_{Nt}^j / \Delta t$ as the *marginal utility of waiting* if a type j consumer delays upgrading to the new product. Proposition 1 follows from the characteristics of (6).

Proposition 1 (Consumer demand). Suppose that a consumer owns the old product:

⁶ Previous studies of new product introduction and pricing (e.g., Fudenberg and Tirole 1998; Lee and Lee 1998; Kornish 2001; Nahm 2004; Utaka 2006) typically assume that the new products are available only in the second (last) period, and hence they cannot capture this increasing “urge” of consumers to upgrade. Fishman and Rob’s (2000) overlapping generation model implicitly captures this property, but they focused mostly on R&D choices and homogeneous consumers, and hence they did not provide insights on new product timing and pricing in the presence of price discrimination and market segmentation.

- (i) Her willingness to upgrade to the new product, u_{Nt}^j , increases over time. Further, her marginal utility of waiting increases in the quality of the old product, q_o .
- (ii) If the extent of quality improvement is low ($q_o > 1 - \delta^n$), she obtains higher utility from delaying the upgrade to the new product.
- (iii) A consumer with a higher valuation of product quality, v_j , is more sensitive to changes in upgrade timing.

Figure 1 illustrates the net utility, U_{Nt}^j , that a consumer can obtain from upgrading to the new product over time. Generally, the presence of the installed base of the old product reduces the opportunity “loss” that a consumer incurs from delaying the purchase of the new product. If the quality of the old product is sufficiently high (i.e., $q_o > 1 - \delta^n$), the consumer benefits from postponing the upgrade.

[Insert Figure 1 here]

Proposition 1 results from two forces in the demand dynamics: one is the former patrons’ increasing willingness to upgrade due to the depreciation of their old product, which increases their tendency to upgrade. The other is their benefit from continuing to use the old product for longer periods (relative to getting the new product earlier). This decreases their tendency to upgrade. On balance, their net payoff is a function of the discount factor, extent of quality improvement, and durability. If the quality of the old product is high, the second force would prevail, and consumers would delay their upgrade.

The following two sections consider how an installed base of the old product affects the purchase timing and pricing of the new product.

4.2 Partly-Covered Installed Base

Here we study a setting in which high type consumers have bought and used the old product for one period prior to the beginning of Period 1. Since low type consumers do not own any

product at the beginning of the game, the monopolist vendor has to consider not only the timing and pricing strategies of the new product, but also, whether, when, and how much to sell the old product to low type consumers.

Specifically, the vendor can sell the new product only in Period 1, only in Period 2, or in both periods, and it can offer premium pricing (a high price that is only affordable to one type of consumer), penetration pricing (a low price that is affordable to both consumer types), or intertemporal price discrimination (sell to consumers sequentially). The vendor engages in *delayed introduction* if it chooses to sell the new product only in Period 2.⁷

Also, the vendor needs to decide whether to sell the old product to low types in Period 1 or Period 2. Table 1A summarizes all product line and pricing strategies (denoted as S1, S2, ..., S7), and Table 1B presents the product sequences in each of these strategies. Both Tables 1A and 1B exclude off-equilibrium strategies.⁸

[Insert Tables 1A and 1B here]

Following Proposition 1, Corollary 1.1 characterizes the demand given that only high type consumers own the old product prior to the beginning of Period 1.

Corollary 1.1. With a partly-covered installed base, low type consumers are more impatient than high type consumers when the extent of quality improvement is low ($q_o > 1 - \delta^n$), or their quality valuations are not too heterogeneous ($v_L^H \leq V_3$). If $v_L^H \leq V_1$, low type consumers always get higher utility from the new product than high type consumers.

Table 2 compares high and low type consumers' utilities from the new product, given that only high type consumers own the old product. Two things are worth noting: First, even without considering price, high type consumers would get more utility from the new product

⁷ In Moorthy and Png (1992), the vendor would never sell the old product before the new product because this would aggravate cannibalization. However, as we shall show below, although our setting is similar to Moorthy and Png's, on the condition that there is an existing (partly-covered) installed base of the old product, the vendor may sell the old product first because of different consumer purchase histories.

⁸ Referring to the game tree presented in Appendix B, there are altogether 11 product line strategies, but four of them would not be chosen by the vendor in any parameterizations in equilibrium.

than low type consumers only when the heterogeneity in quality valuation is high enough to overcome the balking effect caused by their holdings of the old product.⁹ Second, due to depreciation of the existing stocks, the relative utility of the two consumer types varies with purchase timing. High type consumers could sometimes be less sensitive to purchase timing, and could get *higher* utility over time if the quality of the old product is high. That is, they may prefer delaying the upgrade. This never happens to low type consumers.

[Insert Table 2 here]

Neither of these findings would arise if all consumers share the same purchase history, i.e., if there is no pre-existing installed base of the old product, but, as we shall illustrate below, they lead to remarkable product line and pricing implications that have not been well explored in the literature. We begin with the scenario when the monopolist vendor cannot offer an upgrade policy, the analysis of which may be of some independent interest as it corresponds to a problem involving intertemporal price discrimination by both valuations for quality and purchase history, but the vendor cannot use an upgrade policy to discriminate consumers by purchase history (cf. Lee and Lee 1998). To our knowledge, this problem has not been analyzed in the previous literature.¹⁰

4.2.1 No Upgrade Policy

In this section we suppose that the vendor cannot offer an upgrade discount to former patrons, perhaps because the administration cost of upgrade is too high, or because the vendor cannot identify former patrons. So, all consumers must pay the same price for the new product.

⁹ In particular, if the heterogeneity is moderate (see the second column in Table 2), the preferences of the two consumer types “cross” over time – in Period 1, low type consumers get more utility from the new product than high type consumers, but this is reversed in Period 2. This preference structure is possible only when there is an existing installed base of the old product, and when the vendor can vary the timing of the new product.

¹⁰ Fishman and Rob (2000) study a similar problem with recurrent product innovations, no upgrade policy, but homogeneous consumers, and hence price discrimination is not an issue in their study. Levinthal and Purohit (1989), Fudenberg and Tirole (1998), and Nahm (2004) study a two-period product line and pricing problem with technological innovations and heterogeneous consumers, but they assume the existence of a frictionless second hand market and hence their consumers would never possess more than one product at the same time, i.e., there is no “economic obsolescence” (Lee and Lee 1998) in their studies.

Since we assumed rational, forward looking consumers, and the vendor cannot make product and pricing commitments, we used backward induction to derive the equilibrium outcomes, the details of which are presented in Appendix B. The pricing of the two products by the vendor is subject to several constraints. First, the installed base of the (still functional) old product reduces the price that high type consumers are willing to pay for the new product. Second, since the vendor cannot price discriminate consumers by purchase history, if it wants to sell the new product to all consumers in the same period, it has to set a common (low) price even if low type consumers are willing to pay more (which is possible by Corollary 1.1). Third, the vendor may continue to sell the old product to low type consumers, the price of which would be restricted by the price of the new product. The links between these pricing constraints produce a wide variety of equilibrium outcomes.

In a similar setting with a partly-covered installed base and where the new product is sold for only one period, previous research has variously found (or sometimes assumed) that the vendor would always sell the new product to high valuation consumers when there exists a frictionless second hand market and the demand is continuous. Whether the vendor would continue to sell the old product to low valuation consumers depends on demand distributions and the relative quality of the old and new products (Levinthal and Purohit 1989; Fudenberg and Tirole 1998; Kornish 2001; Nahm 2004; Sankaranarayanan 2007).

In view of these findings, we ask two questions: Suppose that there is no second hand market and so consumers cannot resell their old products, and, the vendor can plan for both the old and new products over two periods (instead of one) with high type consumers already owning the old product. Would the vendor always sell the new product immediately? Would high type consumers always buy the new product before low type consumers?

Interestingly, the next few propositions show that the answers to these two questions are sometimes “no”.

Proposition 2 (Infeasibility of restricting the new product to high types in Period 1). If $q_o > 1 - \delta^n$, the vendor would not sell the new product only to high type consumers (strategy S3) or sell the new product to high type consumers and old product to low type consumers (strategy S2) in Period 1.

Note that $q_o > 1 - \delta^n$ would likely hold when the extent of quality improvement is not too high (i.e., q_o is not too small), the discount factor, δ , is not too small, and the number of period, n , is not excessively large.

In fact, as we illustrate in Appendix B (Table B9), even if $q_o \leq 1 - \delta^n$, there is only a small set of parameters in which strategies S2 and S3 could be optimal for the vendor. These results imply that the common finding (or assumption), that the vendor would always sell the new product immediately only to some high type consumers (Levinthal and Purohit 1989; Fudenberg and Tirole 1998; Kornish 2001; Nahm 2004), is often not tenable. Further, on the condition that high type consumers own the old product prior to the beginning of the game, strategies such as “simultaneous introduction” (sell the old and new products in Period 1 to different consumers) or “sequential introduction” (sell the new product in Period 1 to high types and old product in Period 2 to low types) (Moorthy and Png 1992) which had received some attention in the literature may not be likely equilibrium outcomes.¹¹

The intuition behind Proposition 2 (i.e., the difficulty of selling only to high types in Period 1) is as follows. The vendor suffers from the classical time inconsistency problem in pricing the new product (Coase 1972); high type consumers would expect the vendor to sell

¹¹ Notwithstanding the results in Proposition 2, it is worth pointing out that should the vendor choose strategy S3 when $q_o \leq 1 - \delta^n$, the price of the new product would decrease over time. High type consumers, despite already owning the old product, would still self-select to buy the new product at a higher price in Period 1. This result is intriguing because previous studies have mostly suggested that if high valuation consumers already own the old product, without direct price discrimination, it is impossible for the vendor to charge them a new product price in excess of the regular price that it charges for low valuation consumers (Fudenberg and Tirole 1998; Lee and Lee 1998). Here, with multiple periods, high type consumers may be so impatient that they would not want to wait for the cheaper price in Period 2 (i.e., they would not arbitrage even when it is technically feasible for them to do so).

the new product at lower price to low types in Period 2. So, the vendor must reduce the price that it charges in Period 1 so as to let high type consumers keep some surplus. This, however, would attract low type consumers to buy the new product in Period 1.

To dissuade low type consumers from buying the new product in Period 1, the vendor could sell the old product to them at a very low price (the intuition here is similar to Moorthy and Png 1992), but this would reduce their need to buy the new product in Period 2. Overall, if the vendor has an option to sell the new product later, it is difficult for it to restrict output to only high types or practice static price discrimination using different products in Period 1 (despite high type consumers own the old product prior to the beginning of the game).

Proposition 2 shows the importance of game structure in shaping previous findings – our model departs from previous studies in that we removed the assumption of the existence of a frictionless second hand market (cf. Levinthal and Purohit 1989; Fudenberg and Tirole 1998; Nahm 2004), allowed the vendor to extend the decision horizon to beyond one period after the new product is introduced, and did not pre-set product sequences (cf. Moorthy and Png 1992; Dhebar 1994; Kornish 2001). All of these points of departure are not unrealistic, but yet they lead to results that are distinctive from the previous literature.

The next result has important theoretical and practical implications. Instead of selling the new product to high type consumers first, the vendor may choose to sell only to low type consumers in Period 1, followed by high type consumers in Period 2. More importantly, in some cases, this strategy extracts all consumer surplus.

Proposition 3 (Perfect intertemporal price discrimination). If and only if

$$(i) \ q_o \leq 1 - \delta^n \text{ and } V_1 < v_L^H \leq \frac{d_L[1 - \delta^n]}{[1 - \delta^n - q_o][1 - \delta] + \delta d_L \{1 - \delta^n - q_o[1 - \delta^{n-2}]\}}, \text{ or}$$

$$(ii) \ q_o > 1 - \delta^n \text{ and } V_1 < v_L^H \leq V_2,$$

the vendor would extract all surplus by selling the new product only to low type consumers in Period 1, followed by only high type consumers in Period 2 (strategy S4).

Corollary 3.1. When perfect intertemporal price discrimination occurs, the nominal price of the new product always increases over time. The discounted price of the new product also increases over time if $v_L^H > V_1 / \delta$.

The intuition of Proposition 3 is as follows. High type consumers already own the old product prior to Period 1, and so their utility for the new product does not drop too quickly (it can even increase when $q_o > 1 - \delta^n$) over time. If $v_L^H > V_1$, i.e., the valuations for quality are sufficiently different, the vendor would actually *raise* the price of the new product. Low type consumers would buy in Period 1 despite getting negligible surplus because they would face an even higher price (and hence get negative surplus) in Period 2.

Further, if $v_L^H \leq V_2$, the possession of the old product reduces the need of high type consumers for the new product. So, high type consumers are not willing to buy in Period 1 although the price is lower than that in Period 2. They would buy the new product in Period 2 after their old product further depreciates, at the expense of paying a higher price.

Taken together, the vendor could extract all consumer surplus even with self-selection and without any exogenous instrument for price discrimination. This is because the existing installed base of the old product causes the preferences of low type and high type consumers to “cross” over time (see Figure 2), and consumers would self-select into the prices that help the vendor achieve perfect price discrimination.

[Insert Figure 2 here]

Proposition 3 and Corollary 3.1 provide a new perspective for the paradoxical strategy of “limited period promotion for new customers”. While some may variously attribute such a strategy to building a critical mass (Rogers 1995) or cultivating network effects (Katz and Shapiro 1986), our analysis shows that price discrimination could be an important underlying

reason behind such a strategy for products that feature recurrent technological innovations. The vendor may maximize its profit simply by setting the right price at the right time, without needing explicit price discrimination instruments.

In the next proposition, we show that the vendor may deliberately postpone selling the new product.

Proposition 4 (Delayed product introduction). If and only if

$$(i) \quad v_L^H \leq \left[2 - \frac{1}{\delta}\right] d_L V_1; \text{ or}$$

$$(ii) \quad q_o \leq 1 - \delta^n, \text{ and } \frac{1 - d_L q_o}{[1 - d_L] \delta} V_1 < v_L^H \leq V_3$$

$$\text{or } v_L^H > \frac{\delta - d_L q_o}{1 - d_L} \cdot \frac{1 - \delta^n}{q_o [1 - 2\delta + \delta^{n-1}] - [1 - \delta^n][1 - 2\delta]} > V_3; \text{ or}$$

$$(iii) \quad q_o > 1 - \delta^n \text{ and } v_L^H > \frac{1 - d_L q_o}{[1 - d_L] \delta} V_1,$$

the vendor would sell the new product only in Period 2 (strategies S6 and S7).

Corollary 4.1. Consumers always get zero surplus when delayed product introduction occurs.

When consumers are homogeneous or there are relatively few high type consumers in the population (i.e., condition (i) in Proposition 4), the vendor would be better off not selling any product in Period 1. Since high type consumers already own the old product, their utility from the new product is lower than that of low types, and so cannibalization would prevent the vendor from selling the new product to both consumer types in Period 1 (and, obviously it would not sell only to high types in this case too). Similarly, if the vendor sells the new product only to low types in Period 1, they would envisage that the same product would be sold to high types in Period 2 at a lower price. Hence they are reluctant to pay a high price in Period 1 (i.e., the Coase's time inconsistency problem, but applying to low type consumers). To circumvent this, the vendor would deliberately delay selling the new product.

On the other hand, if consumers are sufficiently heterogeneous (i.e., conditions (ii) and (iii) in Proposition 4), the vendor would focus on high type consumers. But, if it sells the new product to high type consumers in Period 1, they would anticipate a reduced price in Period 2 and so be reluctant to pay a high price (the reasoning here is similar to that in Proposition 2, i.e., time inconsistency). To overcome this, the vendor would delay selling the new product. At the same time, because consumers are heterogeneous, the vendor can sell the old product to low type consumers without inducing significant cannibalization because high types already own the old product (it would, however, not sell the new product to low types because of both time inconsistency and cannibalization).

It is instructive to observe that when the extent of quality improvement is low (i.e., $q_o > 1 - \delta^n$), with respect to Propositions 2 to 4, (a) the strategy of selling the new product to high types followed by low types ceases to be optimal in any parameterizations, (b) perfect intertemporal price discrimination becomes even more feasible, and (c) it is more likely for the vendor to delay selling the new product. In general, when quality improvement is low, the vendor may shift its attention to low type consumers rather than high types, which is the underlying reason behind these observations.

We next consider social efficiency. An equilibrium is socially efficient if consumer utility is maximized given the cost of producing the items (Moorthy and Png 1992). In our setting, the marginal cost of production is zero. For each type j consumer, at the beginning of Period 1, her total utilities (including consumption of the old product) from getting the new product in Period 1 and Period 2 are respectively:

$$U_1^j = \frac{v_j[1 - \delta^n]}{1 - \delta}, \quad (7)$$

$$U_2^j = v_j q_o + \frac{\delta v_j [1 - \delta^n]}{1 - \delta}. \quad (8)$$

Subtracting U_2^j from U_1^j , $U_1^j \geq U_2^j$ if and only if $q_o \leq 1 - \delta^n$. Hence, when the extent of quality improvement is high ($q_o \leq 1 - \delta^n$), social optimality requires selling the new product to both consumer types immediately in Period 1 (i.e., strategy S1). Conversely, when the extent of quality improvement is low ($q_o > 1 - \delta^n$), social optimality requires selling the old product to low type consumers in Period 1, followed by the new product to all consumers in Period 2 (i.e., strategy S5). Our next proposition follows.

Proposition 5 (Social inefficiency). For all:

- (i) $q_o > 1 - \delta^n$; or
- (ii) $q_o \leq 1 - \delta^n$, and $v_L^H \leq d_L V_3$,

$$V_1 < v_L^H \leq \frac{d_L [1 - \delta^n]}{[1 - \delta^n - q_o][1 - \delta] + \delta d_L \{1 - \delta^n - q_o [1 - \delta^{n-2}]\}}, \frac{1 - d_L q_o}{[1 - d_L] \delta} V_1 < v_L^H,$$

$$v_L^H > \frac{V_3}{1 - d_L}, \text{ or } v_L^H > \frac{1}{[1 - d_L][1 - \delta^n - q_o]} \left\{ 1 - \delta^n - q_o \left[d_L - \frac{\delta [1 - \delta^{n-1}]}{1 - \delta} \right] \right\},$$

the vendor's equilibrium strategies lead to socially inefficient outcomes.

Corollary 5.1. For all conditions in case (ii), and when $q_o > 1 - \delta^n$ and

$$V_2 < v_L^H \leq \frac{1 - d_L q_o}{[1 - d_L] \delta} V_1,$$

high type consumers are inefficiently served in equilibrium.

Proposition 5 results mainly from time inconsistency and cannibalization. When the extent of quality improvement is high ($q_o \leq 1 - \delta^n$), consumers would prefer to enjoy the new product as soon as possible, but in most cases the vendor would prefer not to serve high type consumers in Period 1 because it can reap more profits from serving low type consumers first. Similarly, when $q_o > 1 - \delta^n$, profit maximization requires the vendor to sell the old product to low types in Period 1, but this would lead to the type of cannibalization similar to Moorthy

and Png (1992) in Period 2, and hence the vendor would prefer to sell the new product earlier than what social optimum would call for.

Previous research has mostly suggested that multiproduct firms would always serve high valuation consumers with efficient products or products with efficient qualities (see, e.g., Mussa and Rosen 1978; Moorthy 1984; Moorthy and Png 1992; Waldman 1996a). However, Corollary 5.1 shows that once high valuation consumers own the old product and the vendor has two periods (instead of one) to sell the new product, it is possible for any consumer to be inefficiently served in equilibrium.

4.2.2 With an Upgrade Policy

We next consider the setting where the vendor can offer an “upgrade policy”, which allows consumers who own the old product to buy the new product at a cheaper price.¹² In general, the upgrade policy presents the vendor an extra instrument to exercise price discrimination based on purchase history (Fudenberg and Tirole 1998; Lee and Lee 1998); the price of the new product is no longer constrained by the utility of consumers who do not possess the old product, and hence the vendor’s profit would (weakly) improve compared with the profits in the setting in which it cannot offer an upgrade policy.

In our setting, only high type consumers possess the old product at the beginning of Period 1. The upgrade policy helps the vendor from two perspectives. First, it can now make a credible threat to low type consumers that if they do not buy the old product in Period 1, they will face a high price of the new product in Period 2 (“high” in the sense that they would get zero surplus if they postpone their purchase until Period 2). This credible threat would dissuade low type consumers from leapfrogging (i.e., skipping the old product in anticipation

¹² Our upgrade policy setting corresponds to the one studied in Lee and Lee (1998), and the “semianonymous” case in Fudenberg and Tirole (1998). The essential features are: (1) consumers must present the old product to purchase the new product at the upgrade price, and (2) consumers can arbitrage – if the upgrade price is too high, consumers who own the old product can pretend to be nonpatrons and buy the new product at the (lower) price meant for new patrons.

of the new product). Hence, the upgrade policy eliminates the cannibalization of the old product by the (forthcoming) new product, and so improves the profitability of strategies that sell both products to consumers (e.g., strategies S2 and S5).

Second, upgrade allows high type consumers to reveal their purchase history if their incremental utility from the new product is lower than that of low types (which is possible by Corollary 1.1). In this case, the vendor can differentiate low and high type consumers and charge low types a higher price for the new product if they do not possess the old product. In other words, the upgrade policy facilitates both intra- and intertemporal price discriminations. Generally, we expect it to improve the profitability of strategies that sell the new product to all consumers when some of them do not own the old product (e.g., strategies S1 and S4).

We first examine the robustness of Propositions 2 to 5.¹³ As we discussed above, the upgrade policy facilitates selling the old product to low type consumers and intra-temporal price discrimination, and so it does not particularly encourage the vendor to restrict the new product to high type consumers in Period 1. Hence, Proposition 2 and the related discussions continue to apply, i.e., both S2 and S3 are off the equilibrium path when $q_o > 1 - \delta^n$. They are equilibrium strategies only for a small set of parameters when $q_o \leq 1 - \delta^n$.

Next, Proposition 3 concerns about perfect intertemporal price discrimination. When $q_o \leq 1 - \delta^n$, i.e., the extent of quality improvement is high, the vendor would prefer to sell the new product as soon as possible. Previously, without upgrade policy, the (uniform) price of the new product is constrained by the utilities of both high and low type consumers, and so the vendor may exploit the dynamic changes in utilities – particularly the higher utility of low type consumers in Period 1 – in maximizing its profits.

¹³ For brevity, we do not present some of the following discussions as formal propositions or corollaries, and we omit the equilibrium parameterizations from the paper. Interested readers may refer to Appendix B for the actual conditions in the equilibria.

Now, with an upgrade policy, the vendor can effectively set different prices even in Period 1, which encourages selling the new product immediately to high types even though they enjoy a lower utility relative to low types. Hence, it does not need to price discriminate against high types over time when $q_o \leq 1 - \delta^n$. Note that in this case the vendor earns even more profits by practicing intra-temporal (or static) price discrimination.

When $q_o > 1 - \delta^n$, i.e., the extent of quality improvement is low, the vendor would be better off letting high type consumers continue to use the old product, because, as explained in Proposition 3, their utility for the new product would increase over time. Hence, perfect intertemporal price discrimination continues to be feasible. The following corollary presents the new parameters for perfect intertemporal price discrimination to occur.

Corollary 3.2. With an upgrade policy, the vendor extracts all consumer surplus by selling the new product to low type consumers in Period 1 and to high type consumers in Period 2 (strategy S4) if and only if $q_o > 1 - \delta^n$ and

$$\frac{V_1}{d_H V_2} - \frac{d_L [1 - q_o]}{[1 - d_L] \delta} V_1 < v_L^H \leq V_2. \quad (9)$$

Given that the upgrade policy enables the vendor to charge different prices for the new product, the motivation behind condition (i) in Proposition 4, viz., the inability to set a high uniform price for the new product in Period 1, no longer holds. So, when $q_o \leq 1 - \delta^n$ and consumers are homogeneous, the vendor would immediately sell the new product at two different prices (i.e., there would not be delayed introduction).

However, when the extent of quality improvement is low, i.e., $q_o > 1 - \delta^n$, although the vendor could still sell the new product to all consumers at different prices in Period 1, it would prefer selling the old product to low type consumers first. The old product would allow low type consumers to buy the new product in Period 2 at a discounted price, while still enabling the vendor to earn a good profit from the new product in Period 2. Since the extent

of quality improvement is low, the vendor would not suffer from the delayed revenue from the new product. Hence, delayed product introduction continues to be a feasible equilibrium outcome when $q_o > 1 - \delta^n$ and consumers are relatively homogeneous.

Finally, when consumers are sufficiently heterogeneous (i.e., v_L^H is large), regardless of the extent of quality improvement, the similar reasoning after Proposition 4 for conditions (ii) and (iii) applies. That is, the vendor would delay selling the new product until Period 2, and would sell the old product to low type consumers in Period 1 (i.e., strategies S5 or S6). The underlying motivation is time inconsistency.

Similar to the case with no upgrade policy, even if the vendor is able to implement an upgrade policy, when the extent of quality improvement is low ($q_o > 1 - \delta^n$), (a) the strategy of selling the new product to high types followed by low types cannot be optimal, (b) perfect intertemporal price discrimination becomes feasible in equilibrium, and (c) the vendor would more likely delay selling the new product. In other words, all our major results continue to apply regardless of whether upgrade policy is used or not.

For social efficiency, since upgrade pricing facilitates selling the new product earlier, when the extent of quality improvement is high ($q_o \leq 1 - \delta^n$), the vendor would always sell the new product to all consumers immediately when consumers are homogeneous ($v_L^H \leq V_2$). That is, the equilibrium outcomes would be socially efficient. When consumers are rather heterogeneous, however, the vendor would continue to postpone selling the new product to some consumers (see Table B18 in Appendix B).

On the other hand, when the extent of quality improvement is low ($q_o > 1 - \delta^n$), in various parameterizations the vendor would choose a strategy that leads to socially optimal outcomes (cf. Proposition 5 wherein the outcomes are always inefficient when $q_o > 1 - \delta^n$).

Hence, upgrade policy could sometimes enhance social efficiency. However, it may not be particularly good for some consumers, as we show in Corollary 5.2.

Corollary 5.2. With an upgrade policy, low type consumers always get zero surplus.

Nevertheless, although an upgrade policy enhances welfare and increases the vendor's profits, it is not omnipotent. In particular, when consumers are sufficiently heterogeneous so that $v_L^H > V_2$, the vendor cannot fully price in high type consumers' incremental utility from the new product; in this case, high type consumers could arbitrage and conceal their purchase history. So, consistent with the previous literature (e.g., Fudenberg and Tirole 1998; Lee and Lee 1998), there are parameterizations in which a uniform price for the new product would be imposed whether upgrade policy is used or not (e.g., when $q_o \leq 1 - \delta^n$ and $v_L^H > V_2$).

Departing from previous studies, however, in addition to setting a uniform price, the vendor could also exercise intertemporal price discrimination (strategy S3), delayed product introduction (strategy S6), or both intra- and intertemporal price discrimination by offering a low upgrade price to high type consumers while selling the entire product line to low types (strategy S2). These strategies could help the vendor retain some price discrimination power when upgrade policy loses its merit in distinguishing consumers. They are feasible primarily because the vendor has more than one period in selling the new product.

Note, however, that this price discrimination power comes with a cost – they always cause some consumers to be inefficiently served, unlike the case when the vendor can only set a uniform price for the new product and sell it immediately (which is socially efficient when $q_o \leq 1 - \delta^n$).

4.2.3 Endogenizing Upgrade

In general, the upgrade policy provides the vendor an extra instrument to price discriminate consumers, and so it leads to profits that weakly dominate those in the case with no upgrade

policy. The vendor could either directly price discriminate consumers, or even if it does not, the upgrade policy serves as a credible threat to affect consumers' purchase sequences. The following proposition summarizes the impact of the upgrade policy:

Proposition 6 (Use of Upgrade Policy).

- (i) When $q_o \leq 1 - \delta^n$ and $v_L^H \leq V_2$, the vendor would use the upgrade policy and sell the new product in Period 1 to all consumers at different prices.
- (ii) When $q_o > 1 - \delta^n$ and

$$v_L^H \leq \frac{V_1}{d_H V_2} - \frac{d_L [1 - q_o]}{[1 - d_L] \delta} V_1,$$

the vendor would offer the upgrade policy, but the upgrade option would not be exercised in equilibrium. However, it causes low type consumers to buy the old product earlier and so helps the vendor to earn higher profits.

Nevertheless, timing may sometimes outperform the upgrade policy as an instrument to differentiate consumers. Corollary 6.1 highlights this finding.

Corollary 6.1. For the parameters in (9), the vendor could use the upgrade policy to price discriminate consumers, but it would rather use intertemporal price discrimination instead of upgrade policy in equilibrium.

Corollary 6.1 is the first result to show that a monopolist vendor may not exploit an explicit instrument for price discrimination, viz., upgrade policy, even when consumers are sufficiently homogeneous that renders price discrimination feasible. This is caused by the combination of the installed base and the extended decision horizon in our model (cf. prior research which typically incorporates one decision period with no installed bases).

4.3 Fully-Covered Installed Base

In the presence of a fully-covered installed base, both high and low type consumers own the old product at the beginning of the game. The vendor only needs to consider the timing and

pricing of the new product. Unlike the case with partly-covered installed base, now the high type consumers' reservation price for the new product is always higher than that of low type consumers in both periods. Hence, they are more sensitive to changes in purchase timing (as characterized in Proposition 1).

In this case, high type consumers would always be served first. Whether the vendor would choose penetration pricing, premium pricing, or intertemporal price discrimination depends on the extent of consumer heterogeneity, quality improvement, and the relative sizes of high type and low type populations. However, in some extreme cases in which consumer valuations increase over time (mostly because the quality improvement of the new product is small), it is possible for the vendor to postpone selling the new product to all consumers. The intuition here is essentially the “demand accumulation” effect (see, e.g., Dhebar 1994; and Kornish 2001) rather than time inconsistency as we discussed after Proposition 4.

5. Concluding Remarks

We study the timing and pricing of a new product given that there has been an installed base of some old product, and the vendor can continue to sell the old product over time. Instead of focusing on strategies such as buyback, upgrade, or reducing durability which mostly concern the old product (see, e.g., Bulow 1986; Levinthal and Purohit 1989; Waldman 1993; 1996a; 1996b; Fudenberg and Tirole 1998; Nahm 2004), we emphasize that the valuation of former patrons toward the new product is dynamic, and that it varies according to the characteristics of the consumers and product quality. We show that some well-known results in the existing literature may not be robust in view of such dynamic valuation.

Our results revitalize the importance of intertemporal price discrimination even when the vendor cannot directly identify and segment consumers (Stokey 1979). In some cases, the vendor could increase the price of the new product over time while capturing all surplus from consumers. Intertemporal price discrimination may also outperform upgrade pricing even

when the latter is practically feasible for the vendor. We found that in a variety of cases the vendor would delay selling the new product. Such delayed introduction is an effective way to address the time inconsistency problem in durable goods pricing. Unfortunately, the vendor's strategies often lead to socially undesirable consequences.

How are our results relevant to real-life practices? As mentioned earlier, we observe experiences of Sony, Apple, etc., that seem to be consistent with the strategic choices studied in this paper. Further, Figure 3 plots the average prices of several consumer durables (home electrical appliances) over time in the United States. While the prices of several products occasionally decreased, many of them increased over the years. It is worth noting that the markets for these home durables tend to be quite concentrated. So, the price increases could have happened because the vendors exercised their (intertemporal) pricing power in selling overlapping generations of these home durables.¹⁴

[Insert Figure 3 here]

Similarly, it appears that delayed introduction of new products had occurred among some durable products. For example, the technologies for wideband third-generation (3G) mobile telephone services had been available since many years ago, but to-date many service providers are still focusing their businesses on second-generation cellular services. Some software vendors like Microsoft had been pushing back selling new versions of their software. While it was possible that the new products were not yet mature, it could well be that the vendors were maximizing profits by tackling time inconsistency and cannibalization through the kind of delayed introduction strategies that we proposed here.

The findings in this paper also suggest that policy makers could play a role to enhance social efficiency. In particular, when the extent of quality improvement embodied in a new product is low, they should encourage consumers to retain their old products. This could be

¹⁴ Figure 3 plots the nominal prices over time, but the inflation-adjusted price trends are similar. Obviously, many alternative explanations may account for these increasing prices. We present Figure 3 merely to illustrate that price increase over time is not uncommon in empirical markets of durable products.

achieved by increasing the transaction costs for selling the new product, or, in cases where the new product requires exclusive licenses (e.g., 3G cellular phones), by postponing granting the necessary licenses to the vendors.

On the other hand, when the extent of quality improvement is high, the policy makers could encourage new product purchases by promoting trade-ins or using upgrade discounts (Fudenberg and Tirole 1998; Lee and Lee 1998; Nahm 2004), or by levying higher taxes on using old products. The latter approach is common for automobiles – in some countries, substantial tax discounts are offered for environment-friendly new cars (cf. old cars which are less fuel efficient and generate more pollution).

Future research may extend this study in several obvious ways. First, an immediate question is whether our results are robust in a competitive market, or a market with new entrants. Second, one could incorporate other factors, such as seasonal or myopic demands, asymmetric quality information, network effects, or positive marginal costs. It may also be helpful to endogenize the formation of the installed base. The challenge in these extensions lies in ensuring the tractability of the analysis since the vendor's candidate timing and pricing strategies may increase exponentially.

Finally, although we suggested some anecdotal examples that seem to be consistent with our theory, it is worthwhile to empirically test the implications of this research, e.g., the relationship between the extent of quality improvement and strategic choices of the vendor, using large-scale market data.

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Appendix A.

Proof of Proposition 1. From (3),

$$u_{N[t+1]}^j - u_{Nt}^j = v_j q_o \delta^{n-[t+1]} > 0, \quad (\text{A1})$$

and from (6),

$$\frac{d(\Delta U_{Nt}^j / \Delta t)}{dq_o} = \frac{\delta^{t-1}[\delta^{\Delta t} - 1]}{\Delta t} \cdot \frac{-v_j}{1-\delta} > 0 \quad (\text{A2})$$

since $\delta < 1$. (A1) and (A2) prove part (i). Part (ii) is obvious from (6). For part (iii), by (4),

$U_{Nt}^H > U_{Nt}^L$, and by (6), if $q_o > Q_2$,

$$0 < \frac{\Delta U_{Nt}^L}{\Delta t} \leq \frac{\Delta U_{Nt}^H}{\Delta t},$$

whereas if $q_o \leq Q_2$,

$$\frac{\Delta U_{Nt}^H}{\Delta t} \leq \frac{\Delta U_{Nt}^L}{\Delta t} \leq 0.$$

Taken together, $\text{abs}(\Delta U_{Nt}^H / \Delta t) \geq \text{abs}(\Delta U_{Nt}^L / \Delta t)$, i.e., the *magnitude* of the marginal utility of waiting is always larger for high type consumers. []

Proof of Corollary 1.1. If $q_o > Q_2$, it is obvious from (5) and (6) that

$$\frac{\Delta B_{Nt}^L}{\Delta t} < 0 < \frac{\Delta U_{Nt}^H}{\Delta t}.$$

On the other hand, if $q_o \leq Q_2$ but $v_L^H \leq V_3$, by (5) and (6)

$$\frac{\Delta B_{Nt}^L}{\Delta t} - \frac{\Delta U_{Nt}^H}{\Delta t} = \frac{\delta^{t-1}[\delta^{\Delta t} - 1]}{\Delta t} \cdot \frac{v_L[1-\delta^n] - v_H[1-\delta^n - q_o]}{1-\delta} < 0.$$

Finally, if $v_L^H \leq V_1$, by (2) and (4), for all $t \leq 2$,

$$B_{Nt}^L - U_{Nt}^H = \delta^{t-1} \left\{ \frac{v_L[1-\delta^n] - v_H\{1-\delta^n - q_o[1-\delta^{n-t}]\}}{1-\delta} \right\} > 0. \quad []$$

Proof of Proposition 2. Referring to Appendix B, Table B10, when $q_o > 1 - \delta^n$, both strategies S2 and S3 are eliminated from the set of equilibrium strategies. []

Proof of Proposition 3. Referring to the fifth row in Table B9, Appendix B, if $q_o \leq 1 - \delta^n$, then the vendor would choose strategy S4 ($1: N \rightarrow L; 2: N \rightarrow H$) whenever

$$V_1 < v_L^H \leq \Phi_1 \equiv \frac{d_L[1 - \delta^n]}{[1 - \delta^n - q_o][1 - \delta] + \delta d_L\{1 - \delta^n - q_o[1 - \delta^{n-2}]\}}. \quad (\text{A3})$$

(The vendor would not choose strategy S4 in $\Phi_1 < v_L^H \leq V_2$ not because it cannot perfectly price discriminate consumers, but because it would be better off selling the new product immediately to all consumers in Period 1).

Similarly, referring to the fourth row in Table B10, if $q_o > 1 - \delta^n$, the vendor would choose strategy S4 when $V_1 < v_L^H \leq V_2$, and it extracts all consumer surplus. []

Proof of Corollary 3.1. By (B3) and (B9),

$$p_2^N - p_1^N = \frac{v_H\{1 - \delta^n - q_o[1 - \delta^{n-2}]\}}{1 - \delta} - \frac{v_L[1 - \delta^n]}{1 - \delta} > 0$$

whenever $v_L^H > V_1$. Further, $\delta p_2^N > p_1^N$ if and only if $v_L^H > V_1 / \delta$. []

Proof of Proposition 4. Referring to the first row in Tables B9 and B10, the vendor would choose strategy S7 ($1: -; 2: N \rightarrow L$) whenever condition (i) holds. Similarly, referring to the eighth and last rows in Table B9, and the last row in Table B10, the vendor would choose strategy S6 ($1: O \rightarrow L; 2: N \rightarrow H$) when conditions (ii) and (iii) hold. In all of these cases, the new product is sold only in Period 2. []

Proof of Corollary 4.1 Trivial by the last column in Tables B9 and B10. []

Proof of Proposition 5. Referring to Table B10, strategy S5 ($1: O \rightarrow L; 2: N \rightarrow H \& L$) is not an equilibrium strategy in any parameterization. Similarly, referring to Table B9, strategy

S1 ($1: N \rightarrow H \ \& \ L; 2: -$) is not the equilibrium strategy in the parameterizations specified in condition (ii) of the Proposition. []

Proof of Corollary 5.1. For all the conditions in (ii), the vendor would not sell the new product to high type consumers in Period 1, which means that high types are inefficiently served. Similarly, when $q_o > 1 - \delta^n$ and

$$V_2 < v_L^H \leq \frac{1 - d_L q_o}{[1 - d_L] \delta} V_1,$$

the vendor would prefer to sell the new product to high type consumers immediately in Period 1, which is not socially optimal. []

Proof of Corollary 3.2. Referring to the second row in Table B19, if $q_o > 1 - \delta^n$, then the vendor would choose strategy S4 ($1: N \rightarrow L; 2: N \rightarrow H$) if and only if

$$\frac{V_1}{d_H V_2} - \frac{d_L [1 - q_o]}{[1 - d_L] \delta} V_1 < v_L^H \leq V_2. \quad [] \quad (9)$$

Proof of Corollary 5.2. Trivial by the last column in Tables B18 and B19. []

Proof of Proposition 6. By comparing the vendor's profit in the first row in Table B18 with those in the first six rows in Table B9, when $v_L^H \leq V_2$, using (B17), we have

$$\begin{aligned} & \frac{d_L v_L [1 - \delta^n]}{1 - \delta} + \frac{d_H v_H \{1 - \delta^n - q_o [1 - \delta^{n-1}]\}}{1 - \delta} > \frac{\delta d_L v_L [1 - \delta^n]}{1 - \delta}, \\ & \frac{d_L v_L [1 - \delta^n]}{1 - \delta} + \frac{d_H v_H \{1 - \delta^n - q_o [1 - \delta^{n-1}]\}}{1 - \delta} - \frac{\delta v_H \{1 - \delta^n - q_o [1 - \delta^{n-2}]\}}{1 - \delta} - d_L v_L [1 - \delta^n] \\ & = \frac{\delta d_L v_L [1 - \delta^n]}{1 - \delta} - \frac{\delta d_L v_H \{1 - \delta^n - q_o [1 - \delta^{n-2}]\}}{1 - \delta} \\ & \quad + \frac{d_H v_H \{1 - \delta^n - q_o [1 - \delta^{n-1}]\}}{1 - \delta} - \frac{\delta d_H v_H \{1 - \delta^n - q_o [1 - \delta^{n-2}]\}}{1 - \delta} \geq 0, \\ & \frac{d_L v_L [1 - \delta^n]}{1 - \delta} + \frac{d_H v_H \{1 - \delta^n - q_o [1 - \delta^{n-1}]\}}{1 - \delta} - \frac{v_H \{1 - \delta^n - q_o [1 - \delta^{n-1}]\}}{1 - \delta} \\ & = \frac{d_L v_L [1 - \delta^n]}{1 - \delta} - \frac{d_L v_H \{1 - \delta^n - q_o [1 - \delta^{n-1}]\}}{1 - \delta} \geq 0, \end{aligned}$$

which completes the proof of part (i). Part (ii) follows from the first row in Table B19 and the analysis before Table B13 in Appendix B. []

Proof of Corollary 6.1. The result is trivial from the second row in Table B19, and the analysis in Case 4.1 in Appendix B. []

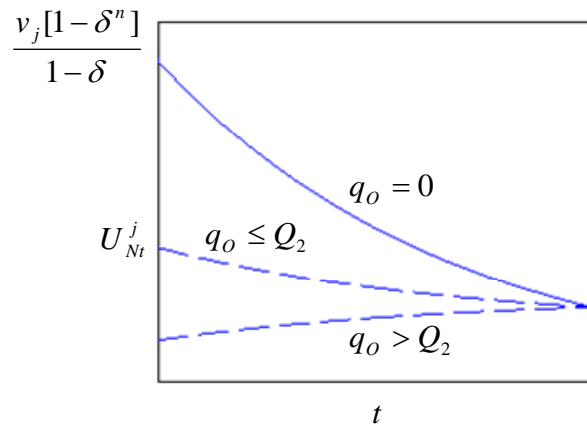


Figure 1. Consumer utility from the new product

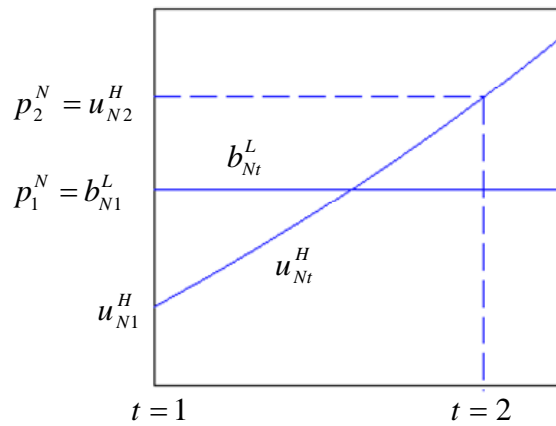


Figure 2. Consumers' willingness to purchase the new product when $V_1 < v_L^H \leq V_2$

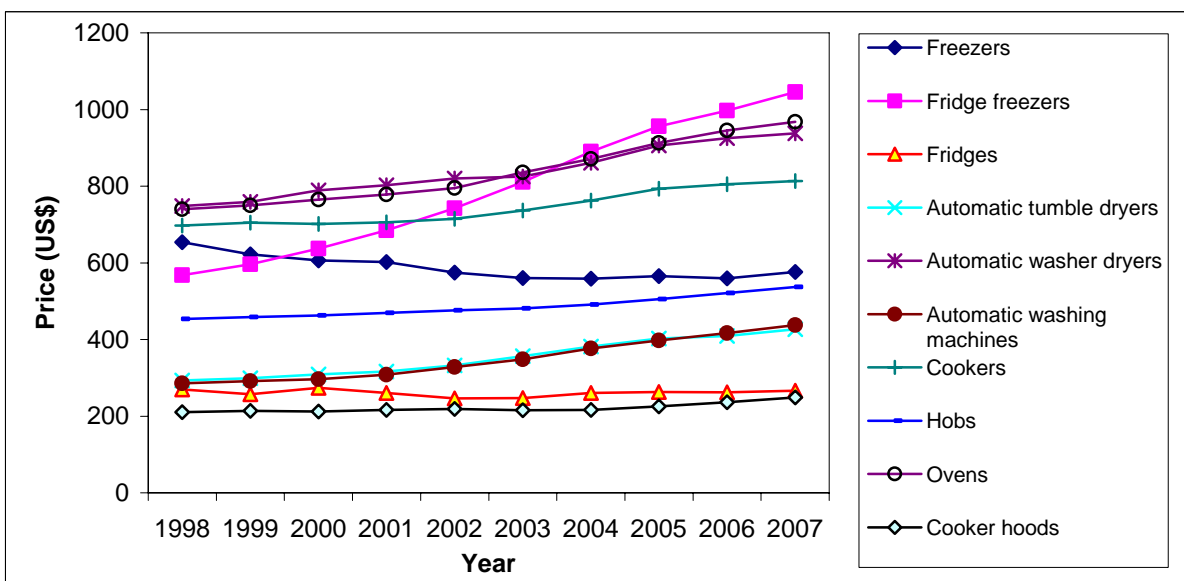


Figure 3. Prices of consumer durables in the USA, 1998-2007

Table 1A. Feasible equilibrium strategies (partly-covered installed base)

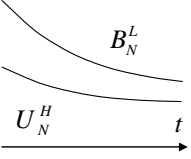
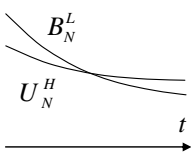
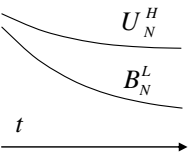
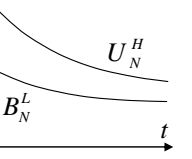
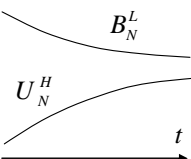
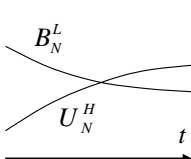
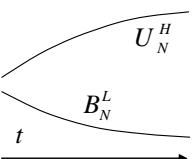
The monopolist vendor's strategies			PRODUCT LINE	TIMING of the new product		
				Period 1 only	Period 2 only	Both periods
PRICING of the new product	Corner solutions	Premium pricing	Both products	-	S6	-
			New product only	-	S7	-
		Penetration pricing	Both products	-	S5	-
			New product only	S1	-	-
	Intertemporal price discrimination	High type followed by Low type	Both products	-	-	S2
			New product only	-	-	S3
		Low type followed by High type	Both products	-	-	-
			New product only	-	-	S4

Table 1B. Equilibrium purchase sequences (partly-covered installed base)

Period	S1		S2		S3		S4		S5		S6		S7	
	H	L	H	L	H	L	H	L	H	L	H	L	H	L
1	N	N	N	O	N	-	-	N	-	O	-	O	-	-
2	-	-	-	N	-	N	N	-	N	N	N	-	-	N

Note: The "N" and "O" indicate whether the high type (H) and low type (L) consumers buy the new product and old product in a particular period in equilibrium.

Table 2. Consumer utilities from the new product (partly-covered installed base)

q_0 \ v_L^H	$v_L^H \leq V_1$	$V_1 < v_L^H \leq V_2$	$V_2 < v_L^H \leq V_3$	$v_L^H > V_3$
$q_0 \leq Q_2$	$U_{N1}^H \leq B_{N1}^L$ $U_{N2}^H \leq B_{N2}^L$ $\frac{\Delta B_{Nt}^L}{\Delta t} \leq \frac{\Delta U_{Nt}^H}{\Delta t} < 0$ 	$U_{N1}^H \leq B_{N1}^L$ $U_{N2}^H > B_{N2}^L$ $\frac{\Delta B_{Nt}^L}{\Delta t} \leq \frac{\Delta U_{Nt}^H}{\Delta t} < 0$ 	$U_{N1}^H > B_{N1}^L$ $U_{N2}^H > B_{N2}^L$ $\frac{\Delta B_{Nt}^L}{\Delta t} \leq \frac{\Delta U_{Nt}^H}{\Delta t} < 0$ 	$U_{N1}^H > B_{N1}^L$ $U_{N2}^H > B_{N2}^L$ $\frac{\Delta U_{Nt}^H}{\Delta t} \leq \frac{\Delta B_{Nt}^L}{\Delta t} < 0$ 
$q_0 > Q_2$	$U_{N1}^H \leq B_{N1}^L$ $U_{N2}^H \leq B_{N2}^L$ $\frac{\Delta B_{Nt}^L}{\Delta t} < 0 \leq \frac{\Delta U_{Nt}^H}{\Delta t}$ 	$U_{N1}^H \leq B_{N1}^L$ $U_{N2}^H > B_{N2}^L$ $\frac{\Delta B_{Nt}^L}{\Delta t} < 0 \leq \frac{\Delta U_{Nt}^H}{\Delta t}$ 	$U_{N1}^H > B_{N1}^L$ $U_{N2}^H > B_{N2}^L$ $\frac{\Delta B_{Nt}^L}{\Delta t} < 0 \leq \frac{\Delta U_{Nt}^H}{\Delta t}$ 	N.A.