

# Entry Deterrence and Innovation in Durable-Goods Monopoly\*

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## Abstract

This paper investigates the efficiency of innovation investments in a durable-goods monopoly when a potential entrant threatens to innovate as well. We show that the durability of the good endows the monopolist with the power to discourage rival innovation since current sales alter the demand for a new generation of the good. The equilibrium is therefore determined not only by competitive pressure due to time inconsistency, but also by the incumbent's concern for maintaining the technological leadership. We demonstrate that entry deterrence followed by no innovation always implies underinvestment in innovation.

*Keywords:* Durable-goods monopoly, Coasian dynamics, entry deterrence, innovation.

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# 1 Introduction

The topic of market structure and innovation has recently experienced a surge of interest from the public and the press during the United States v. Microsoft antitrust case.<sup>1</sup> Although the case centered on the question of whether Microsoft had exercised illegal business strategies in dealing with transaction partners to stifle competition in the software market, Microsoft sidestepped the issue and argued that the durability of its products would introduce enough competitive pressure from its own future output to guarantee both, a competitive outcome in the product market and efficient innovation investments.<sup>2</sup> The logic behind the argument is reminiscent of the Coase conjecture. Coase (1972) argued that a durable-goods monopolist faces a problem of time inconsistency: Once high-valuation consumers have bought, the monopolist will optimally reduce the price. Hence, as price adjustments become more frequent, prices converge to the competitive level. Similar logic is now applied to innovation: Once the old generation of the durable good is sold, the firm must innovate to generate further revenue. In fact, Microsoft promotes the 'freedom to innovate' as a defense strategy.

While previous research on market structure and innovation has tended to focus on non-durable goods,<sup>3</sup> this paper takes up some of the major questions and reexamines them in the context of durable goods in order to gain a better understanding of one of the fundamental issues underlying the antitrust case. In particular, we analyze the effects of product durability on the pricing and innovation behavior of an incumbent monopolist and a potential entrant. Moreover, we investigate whether a durable-goods monopoly under entry threat implements the socially optimal rate of technological progress.

We construct a two-period durable-goods monopoly model with second-period innovation, based on that of Fudenberg and Tirole (1998). The model assumes that the old generation of the durable good lasts two periods so that consumers who buy it in the first period can use it until the second period. In contrast to Fudenberg and Tirole, innovation is endogenous in our model. Furthermore, we introduce a potential entrant who can invent and introduce the new generation of the durable good, characterized by higher quality, just like the incumbent monopolist. The analysis recognizes that innovation by the incumbent monopolist has no preemptive power in deterring entry. If the incumbent innovates, he will optimally respond to rival innovation by

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<sup>1</sup>The case reference is 97-5343: U.S.A. v. Microsoft.

<sup>2</sup>See, for example, the Microsoft Feature Story "Competition in the Software Industry", January 1998, Section C, <http://www.microsoft.com/corpinfo/doj/1-98whitepaper.htm>.

<sup>3</sup>For a comprehensive survey, see Kamien and Schwartz (1982) and Scherer (1992).

withdrawing his own new product. Competition would drive the prices of the new product to zero, whereas the withdrawal generates positive profits for the incumbent from the old product. Instead the incumbent monopolist will always deter entry by means of limit pricing, whenever there is the possibility to do so. Lowering the price of the old generation of the durable good in the first period increases first-period demand and hence the number of second-period consumers who are willing to pay only for the incremental utility derived from the new generation of the product over the old one. Interestingly, we find that limit pricing may prevent the entrant from investing in innovation without necessarily making the same innovation investment unattractive to the incumbent. The reason is that innovation by the potential entrant results in price competition with vertically differentiated products, while innovation by the incumbent yields a multi-product monopoly. In particular, we demonstrate that the entrant would never implement a cross-upgrade policy due to competitive pressure, whereas the multi-product monopolist may find it optimal to offer upgrade discounts in order to price discriminate between former and new customers. As it will turn out, the practice of limit pricing should be carefully assessed. To deter entry, the monopolist charges a lower price compared to the price under no entry threat, while the monopolist may charge an even lower price when entry cannot be deterred. The result follows from the monopolist's incentive to flood the first-period market even when entry is to be conceded.

Our welfare analysis identifies limit pricing as a source of inefficiency in innovation investments. One might argue that, even if limit pricing prevents entry, consumers have already achieved a welfare improvement due to the lower price. By contrast, our model shows that the intertemporal stream of consumers' benefits may not be maximized under limit pricing once the benefits from innovation are taken into account. In particular, we demonstrate that limit pricing leads to underinvestment in innovation whenever the incumbent chooses not to innovate. That is, the social gain from an entrant's innovation always exceeds the entrant's innovation costs in any entry-deterrence equilibrium without innovation. Furthermore, we detect inefficiencies when innovation occurs. Since the possibility to deter rival innovation depends on the demand for the new generation of the durable good and the rival's innovation cost but not on the incumbent's innovation cost, the innovation investment will not necessarily be made by the firm with the least innovation cost.

The model sheds light on a somewhat puzzling aspect of Microsoft's pricing strategy. There is a common consent that Microsoft holds a virtual monopoly in the market for operating sys-

tems. But, as Schmalensee notes, “a real monopolist - one who extracted the last dollar of profit from consumers - would charge hundreds of dollars more for the software that runs modern PCs.”<sup>4</sup> While previous research has pointed to the importance of network externalities,<sup>5</sup> this paper pays attention to yet another dimension of software markets, namely that software is typically a durable good. Like network effects, the effects of the linkage among markets at different points in time due to the durability of software imply that flooding the market may deter entry via a new generation, in this case however not because a consumer’s utility depends on past purchases of other consumers, but on the consumer’s own purchase history.<sup>6</sup> Our welfare analysis indicates that the persistence of a single technological leadership in a durable-goods monopoly threatened by entry does not necessarily imply efficient innovation investments.

The idea that a durable-goods monopolist might fix the time inconsistency problem by introducing a new product has been investigated in different settings by Waldman (1993, 1996), Choi (1994), Fudenberg and Tirole (1998), and Lee and Lee (1998). This literature recognizes the effects of the intertemporal market linkage on the monopolist’s pricing as well as innovation behavior, but abstracts from the existence of a potential entrant.<sup>7</sup> In this paper, we go a step further and show that the intertemporal linkage may introduce inefficiencies in innovation investments when a potential entrant threatens to innovate as well. Although the problem of time inconsistency still influences the equilibrium price path in our model, it is the incentive to discourage rival innovation and thereby prevent entry which is the critical factor determining the equilibrium sales quantity. That the threat of entry may play a role in a durable-goods monopoly is known from Bucovetsky and Chilton (1986) and Bulow (1986) who show that, under certain conditions, the monopolist prefers to sell rather than rent or increase the durability of the good in order to deter entry. The main difference to our model is that we consider entry via a new generation of the good, while the previous papers focus on an entrant who threatens to produce the same good. Related is also the work by Deneckere and de Palma (1998) on a vertically

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<sup>4</sup>See the *Boston Globe*, City Edition, July 10, 1999, p. A17.

<sup>5</sup>See, e.g., Fudenberg and Tirole (2000) on the issue of pricing a network good.

<sup>6</sup>The idea that product durability may be one of the keys to explaining Microsoft’s pricing behavior is supported by Bresnahan’s (1999) observation that radical shifts towards new technology, such as the arrival of the Internet and various Internet technologies, often lead to a weakening of the existing technology’s network effects. For further discussion of the Microsoft case, see, e.g., Gilbert and Katz (2001), Klein (2001), Whinston (2001), and Hoppe and Lee (2001).

<sup>7</sup>Waldman (1996) observes that there may be a time inconsistency problem concerning the innovation decision: The monopolist may invest more in innovation than the amount that maximizes its own profitability, unless the firm can commit to future innovation investments. One can show that for a certain range of parameter values the same result holds in our model when there is no potential entrant.

differentiated durable-goods duopoly in which, however, innovation and upgrade pricing are no issues. Innovation in durable-goods monopoly is considered in recent contributions by Ellison and Fudenberg (2000) and Fishman and Rob (2000). However, in contrast to our paper, their models rule out any Coasian pricing dynamics and do not allow for potential competitors.

The idea behind limit pricing in our model differs from that put forth by Milgrom and Roberts (1982). In Milgrom and Roberts' model, limit pricing is based on asymmetric information between the entrant and the incumbent about the incumbent's cost of production, while our paper assumes complete information. Furthermore, in our paper limit pricing, when exercised, removes the possibility of entry unambiguously. This is consistent with the original idea of limit pricing due to Bain (1949). By contrast, Milgrom and Roberts' result is ambiguous on the probability of entry. Complete-information limit pricing as an entry-deterrence practice has previously been attributed to suppliers of network goods. Fudenberg and Tirole (2000) show that an incumbent may charge low prices to build a large installed base of users of a network good in order to deter entry with an incompatible product. The authors, however, assume away any Coasian pricing dynamics and incentives for upgrade pricing, which are the focus of our analysis. Moreover, in contrast to the existing work on limit pricing, our paper explores the effect of limit pricing on the efficiency of innovation investments.

The paper is organized as follows. In the next section we present a two-period model of a durable-goods monopoly threatened by entry via a new generation of the good. Section 3 analyzes the subgames after the innovation decisions. Section 4 provides the main analysis of the whole game. Section 5 discusses welfare implications, and Section 6 concludes. All proofs are relegated to the Appendix.

## 2 Model

We consider a two-period model of a durable-good market, based on that of Fudenberg and Tirole (1998). In period 1 an incumbent monopolist,  $I$ , produces a durable good, associated with quality level  $s_L$ . The good lasts two periods after which it vanishes. Between period 1 and period 2, the incumbent can invest in innovation, which enables him to produce a new generation of the good, characterized by the higher quality level  $s_H = (s_L + s_\Delta)$ ,  $s_\Delta > 0$ . Hence, conditional on innovation, the incumbent may sell both generations of the good in period 2, the low-quality one and the high-quality one. To ensure uniqueness of the equilibrium, it is

assumed that the quality improvement is not too large:  $s_\Delta < s_L$ . In contrast to Fudenberg and Tirole who treat innovation as exogenous, we endogenize this decision by assuming that the incumbent incurs innovation costs,  $K_I \geq 0$ , if it chooses to innovate. Furthermore, we introduce a potential entrant,  $E$ , who can also invest in innovation and sell the new generation of the good with quality  $s_H$  in period 2. Let  $K_E \geq 0$  be the entrant's innovation costs.<sup>8</sup> Variable costs of production are independent of quality and equal to zero. It is further assumed that firms cannot change the quality when the good is already produced.

On the demand side, there is a continuum of consumers with different utility from the consumption of the durable good. Each consumer is associated with a type  $\theta$  known only to himself. Consumer types are uniformly distributed over the range  $[0, 1]$ . Each consumer may consume at most one unit of the durable good in each period. The consumer of type  $\theta$  gets utility  $s_i\theta$  from the consumption of the good of quality  $s_i$  per period,  $i = L, H$ . There is no externality among the consumers such as a network effect. Consumers and firms have a common discount factor which is normalized to 1. There is no second-hand market.<sup>9</sup>

The timing and nature of decisions by firms and consumers are as follows. At the beginning of period 1, the incumbent sets a price for the original durable good. Consumers choose whether to purchase the good in period 1 or not. Hence, after period 1, the market divides into the following two segments: (i) the “upgrade market”, which consists of the consumers who have purchased the good in period 1 and may want to upgrade in period 2 if that is an option, and (ii) the “new-purchase market”, which consists of the consumers who have not purchased in period 1. Between the end of period 1 and the beginning of period 2, the incumbent and the potential entrant simultaneously choose whether to invest in innovation, which encompasses the invention and introduction of a new generation of the product to the market.<sup>10</sup> Firms observe the outcome of the innovation game instantaneously. At the beginning of period 2, each firm decides whether to withdraw any product that it is able to produce from any market at a small exit cost  $\varepsilon > 0$ ,<sup>11</sup> and sets a price for each product it wishes to offer in any market. In particular,

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<sup>8</sup>The results obtained hold also when the innovation investment  $K_E$  enables the entrant to produce a good with any quality up to  $s_H$ . In such a case, the entrant will always choose  $s_H$ . This follows from domination arguments.

<sup>9</sup>The assumption plays little role. Typically the assumption of no second-hand market is made together with the possibility of upgrade discount to underscore the role of upgrade discounts. See, for instance, Fudenberg and Tirole (1998) and Lee and Lee (1998). When the upgrade discount is not allowed, the presence of second-hand market simplifies the analysis a little since there are fewer cases to be considered. See, for instance, Waldman (1996).

<sup>10</sup>Thus we make the simplifying assumption that the decision to enter and the decision to innovate on the part of the potential entrant are the same decision.

<sup>11</sup>We follow Judd (1985) in allowing for an intermediate exit stage. Exit is assumed to be nearly costless to apply

each potential supplier of the new generation of the good can choose to price discriminate between consumers with respect to purchase history. That is, we allow the incumbent to give an upgrade discount to the consumers in the upgrade market, and the entrant to give a cross-upgrade discount to former customers of the incumbent. This pricing decision is subject to the incentive compatibility constraint that the upgrade price cannot exceed the new purchase price, since consumers in the upgrade market can pretend not to have purchased previously. If the incumbent wishes to offer the original durable good in period 2, he may set a new price for it. Finally, consumers choose in period 2 whether to buy any product that is offered.

We proceed to characterize subgame-perfect equilibria in this game. Working backwards, we start with the examination of the second-period play.

### 3 Second-period sales

The second-period comprises two sales decisions: first, the decision in which market to offer any product that can be produced, and second, the decision of how to price the respective product. All second-period decisions depend on the innovation history and the first-period sales history. The latter can be represented by the type of the cutoff consumer, denoted by  $\theta_1$ , who is indifferent between buying in period 1 and not buying in period 1 due to the following monotonicity property: If the consumer of type  $\theta_1$  prefers to purchase in period 1, then all consumers with type  $\theta \geq \theta_1$  prefer to purchase in period 1 (see Fudenberg and Tirole, 1998 [Lemma 4]). Regarding the innovation history, we need to distinguish among four cases:  $N$  denotes the history in which no firm has innovated;  $I$  and  $E$  denote the histories in which only the incumbent or only the entrant has innovated, respectively; and  $B$  denotes the history in which both firms have innovated. We define four subgames  $\Gamma^N$ ,  $\Gamma^I$ ,  $\Gamma^E$ , and  $\Gamma^B$  for each innovation history, respectively.

In this section, we shall analyze first the optimal second-period behavior of the incumbent in the absence of entry, i.e. subgames  $\Gamma^N$  and  $\Gamma^I$ , and then turn to the second-period equilibrium in the case of entry, i.e. subgames  $\Gamma^E$  and  $\Gamma^B$ .<sup>12</sup>

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Judd's argument of the non-credibility of spatial preemption and thereby obtain a unique solution for the second-period pricing subgame. Without this assumption, a certain parameter range would admit multiple equilibria, where one of them could be part of an entry-deterrence equilibrium similar to that in Gilbert and Newbery's (1983) model of preemptive patenting. But even in that case, the equilibrium that is unique under nearly costless exit would remain an equilibrium.

<sup>12</sup>We collect all computational results in a few tables at the end of the paper.

### 3.1 Second-period behavior in the absence of entry

In subgame  $\Gamma^N$ , i.e. when no firm has innovated, the incumbent may choose to sell the original, low-quality good to consumers who have not purchased in the past, i.e. consumers of types  $\theta < \theta_1$ . Let  $p_L$  denote the second-period price for this good. The incentive constraint for the marginal consumer  $\theta_2$ , who is indifferent between buying and not buying, is given by  $\theta_2 s_L - p_L = 0$ . The incumbent's problem is hence

$$\max_{\{p_L\}} p_L \left( \theta_1 - \frac{p_L}{s_L} \right) \quad (1)$$

subject to

$$\frac{p_L}{s_L} \leq \theta_1. \quad (2)$$

The maximum is attained at  $p_L = s_L \theta_1 / 2$  for  $0 \leq \theta_1 \leq 1$ .

Consider subgame  $\Gamma^I$  in which the incumbent can sell both the old and the new generation of the durable good.<sup>13</sup> Let  $p_U$  and  $p_H$  denote the price of the new, high-quality product offered to consumers in the upgrade market and consumers in the new-purchase market, respectively. A standard result for Mussa-Rosen (1978) type preferences combined with the assumption  $s_\Delta < s_L$ , as used here, implies that a monopolist would not want to use two different varieties in one market. That is, the incumbent finds it optimal to offer either the new or the old product in the new-purchase market. The optimal second-period policy is hence given by

$$\max_{\{p_U, p_H, p_L\}} \left\{ \left(1 - \frac{p_U}{s_\Delta}\right) p_U + \left(\theta_1 - \frac{p_H}{s_L + s_\Delta}\right) p_H, \left(1 - \frac{p_U}{s_\Delta}\right) p_U + \left(\theta_1 - \frac{p_L}{s_L}\right) p_L \right\} \quad (3)$$

subject to

$$\frac{p_U}{s_\Delta} \geq \theta_1 \quad (4)$$

$$\frac{p_H}{s_L + s_\Delta} \leq \theta_1 \quad (5)$$

$$p_U \leq p_H \quad (6)$$

$$\frac{p_L}{s_L} \leq \theta_1 \quad (7)$$

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<sup>13</sup>This subgame has been analyzed by Lee and Lee (1998) for the case of two types of consumers and in part by Fudenberg and Tirole (1998) for a general distribution of consumer types. Our analysis for a uniform distribution of consumer types generates explicit solutions that confirm their results. Moreover, in contrast to Fudenberg and Tirole, we solve the second-period sales problem for the whole range of the first-period sales history which is crucial for the analysis of the first-period equilibrium behavior.



Constraint (4) [(5)] implies that the marginal consumer who is willing to pay  $p_U$  [ $p_H$ ] for the new product belongs to the upgrade [new-purchase] market. Constraint (6) stems from the fact that upgrade consumers can pretend not to have purchased in period 1, and constraint (7) is the same as (2) in subgame  $\Gamma^N$ .

We first solve the maximization problem assuming that the incentive compatibility constraint (6) is not binding. This yields the optimal discriminating prices for the new product:

$$p_U = \begin{cases} \theta_1 s_\Delta & \text{if } \theta_1 > \frac{1}{2} \\ \frac{1}{2} s_\Delta & \text{if } \theta_1 \leq \frac{1}{2} \end{cases} \quad (8)$$

$$p_H = \frac{1}{2}(s_L + s_\Delta)\theta_1. \quad (9)$$

Checking constraint (6) reveals that  $p_U \leq p_H$  for  $\theta_1 > 1/2$  if and only if  $s_\Delta \leq s_L$ , which is satisfied by Assumption (A1). However, for  $\theta_1 \leq 1/2$  we have  $p_U \leq p_H$  if and only if  $\theta_1 \geq s_\Delta / [s_L + s_\Delta]$ . That is, the incumbent will price discriminate between customers with different purchase history if and only if the upgrade market is not too large.

Two effects matter for this result: First, consumers in the new-purchase market are willing to pay  $(s_L + s_\Delta)\theta$ , while those in the upgrade market are willing to pay only  $s_\Delta\theta$  for the incremental utility (the reservation-utility effect). Second, as  $\theta_1$  falls, the marginal consumer to which the firm eventually sells in the new-purchase market has less willingness to pay than high value buyers are willing to pay for the upgrade (the ratchet effect), i.e. the incentive compatibility constraint  $p_U = p_H$  becomes binding. If  $\theta_1$  gets too low, we find that the incumbent benefits from raising the price of the new product and selling it only to upgrading consumers, while first time buyers are sold only the old product. That is, the incumbent price discriminates by offering two different price-quality packages.

The results are summarized in the next proposition. Table 2 and 3 present the equilibrium values of profits and prices.

**Proposition 1** *There exist unique values  $z_1, z_2 \in [0, 1]$ , with  $0 < z_1 < z_2 < 1/2$ , such that the incumbent's optimal sales pattern in subgame  $\Gamma^I$  takes the following form:*

1. *If  $z_2 < \theta_1 \leq 1$ , the incumbent sells the new product in both markets at different prices,  $p_U = \max\{s_\Delta\theta_1, s_\Delta/2\} < p_H = (s_L + s_\Delta)\theta_1/2$ .*
2. *If  $z_1 < \theta_1 \leq z_2$ , the incumbent sells the new product in both markets at a uniform price,  $s_\Delta\theta_1 < p_U = p_H \leq s_\Delta/2$ .*

3. If  $0 \leq \theta_1 \leq z_1$ , the incumbent sells the new product only in the upgrade market at price  $p_U = s_\Delta/2$ , and the old product in the new-purchase market at price  $p_L = s_L\theta_1/2$ .

Before proceeding to the second-period play under entry, we will check whether the equilibrium behavior in subgame  $\Gamma^I$  is characterized by so-called consumer leapfrogging, i.e. the existence of consumers who possess the old product and do not upgrade to the new version, while there are others who have not bought the old version and jump immediately to the new one. Such consumer leapfrogging implies that a consumer with a higher valuation will use a product of lower quality than a consumer with a lower valuation. The result might therefore be of independent interest in the context of technology adoption as discussed in the growth literature (e.g., Parente and Prescott, 1994). The result is stated in the following corollary.

**Corollary 1** *Consumer leapfrogging occurs in  $\Gamma^I$  if  $z_1 < \theta_1 < 1/2$ .*

### 3.2 Second-period behavior under entry

We turn next to subgame  $\Gamma^E$  in which the entrant is the only innovator. The incumbent's strategy set is simply a choice of  $p_L \geq 0$ , the price for the old generation of the durable good. The optimal price is given by

$$\max_{\{p_L\}} \left( \frac{p_H - p_L}{s_\Delta} - \frac{p_L}{s_L} \right) p_L \quad (10)$$

subject to

$$\frac{p_H - p_L}{s_\Delta} \leq \theta_1 \quad (11)$$

By contrast, the entrant's strategy set is composed of the following sales policies. First, the entrant can price discriminate between the consumers in the new-purchase market and those in the upgrade market by giving a cross-upgrade discount,  $p_U < p_H$ . Second, he can charge a uniform price in both markets,  $p_U = p_H$ . Third, he can forego sales in the new-purchase market completely. The entrant's problem is hence

$$\max_{\{p_U, p_H\}} \left\{ \left( 1 - \frac{p_U}{s_\Delta} \right) p_U + \left( \theta_1 - \frac{p_H - p_L}{s_\Delta} \right) p_H, \left( 1 - \frac{p_U}{s_\Delta} \right) p_U \right\} \quad (12)$$

subject to

$$\frac{p_U}{s_\Delta} \geq \theta_1 \quad (13)$$

$$\frac{p_H - p_L}{s_\Delta} \leq \theta_1 \quad (14)$$

$$p_U \leq p_H \quad (15)$$

To solve subgame  $\Gamma^E$ , we first look for a candidate Nash equilibrium in prices, assuming that the incentive compatibility constraint  $p_U \leq p_H$  is not binding. Since the entrant monopolizes the upgrade market, the optimal upgrade price  $p_U$  is the same as given by (8) for subgame  $\Gamma^I$ . By contrast, the entrant faces price competition with vertically differentiated goods in the new-purchase market. The new-purchase price  $p_H$  is therefore chosen as a best response to the incumbent's second-period price:

$$p_H = \frac{1}{2}(s_\Delta \theta_1 + p_L). \quad (16)$$

Likewise, the incumbent sets  $p_L$  as a best response to the entrant's new-purchase price:

$$p_L = \frac{1}{2} \frac{s_L}{s_L + s_\Delta} p_H. \quad (17)$$

Solving the reaction functions (16) and (17) simultaneously yields

$$p_H = 2s_\Delta \frac{s_L + s_\Delta}{3s_L + 4s_\Delta} \theta_1 \quad (18)$$

$$p_L = s_\Delta \frac{s_L}{3s_L + 4s_\Delta} \theta_1 \quad (19)$$

Checking the incentive compatibility constraint  $p_U \leq p_H$  reveals however that  $p_H$  will always be below  $p_U$ . That is, the fully discriminating regime under monopoly disappears under duopoly.

The result indicates that if the new-purchase market is not monopolized a new effect comes into play: Price competition between the entrant and the incumbent in the new-purchase market calls for a low new-purchase price  $p_H$  (the competition effect) such that the incentive compatibility constraint  $p_U \leq p_H$  is always binding. That is, the combination of the competition effect and the ratchet effect outweighs the reservation-utility effect. The competitive pressure hence prevents an entrant from price discrimination between upgrade consumers and new-purchase

consumers, where an incumbent monopolist would have chosen to do so.

Otherwise, qualitatively the same happens under duopoly than under monopoly when  $\theta_1$  is reduced. First, the uniform price  $p_U = p_H$  will fall because of the falling valuations in the market for new sales, up to the point where uniform pricing leads to too large a loss on upgrading customers. Instead of a large quantity at a low price it becomes better to reduce quantity to upgraders at a higher price. The solution has a price jump, similar as in subgame  $\Gamma^I$ .

We summarize the equilibrium behavior in subgame  $\Gamma^E$  in the following proposition. Table 2 and 3 present the equilibrium values of profits and prices.

**Proposition 2** *Subgame  $\Gamma^E$  has a unique equilibrium, which can be characterized as follows. There exist unique values  $x_1, x_2, x_3 \in [0, 1]$ , with  $0 < x_1 < x_2 < 1/2 < x_3 < 1$ , such that:*

1. *The entrant sells the new product in both markets at a uniform price,  $p_H = p_U < s_\Delta \theta_1$  if  $x_3 < \theta_1 \leq 1$ ,  $p_H = p_U = s_\Delta \theta_1$  if  $x_2 \leq \theta_1 \leq x_3$ , and  $s_\Delta \theta_1 < p_H = p_U < s_\Delta/2$  if  $x_1 < \theta_1 < x_2$ .*
2. *The entrant sells the new product only in the upgrade market at price  $p_U = s_\Delta/2$  if  $0 \leq \theta_1 \leq x_1$ .*
3. *The incumbent sells the old product in the new-purchase market for all  $\theta_1 > 0$ .*
4. *The entrant's equilibrium profit is continuous and weakly increasing in  $\theta_1$ .*

Notice that the discontinuity at  $\theta_1 = x_1$  implies an interesting change in the structure of the new-purchase market. For  $\theta_1 > x_1$ , there is price competition with vertically differentiated products, while for  $\theta_1 \leq x_1$ , the new-purchase market is monopolized by the incumbent. It turns out that this change in the market structure plays a crucial role for the results on entry deterrence derived below.

Checking for consumer leapfrogging in subgame  $\Gamma^E$  yields that leapfrogging occurs for a certain range of  $\theta_1$ . The range is similar to that in subgame  $\Gamma^I$ , but it is narrower here.

**Corollary 2** *Consumer leapfrogging occurs in  $\Gamma^E$  if  $x_1 < \theta_1 < x_2$ .*

Consider now subgame  $\Gamma^B$  in which both firms have innovated. In this subgame, the incumbent can sell both goods, the old one and the new one, while the entrant can sell only the

new version. We will demonstrate, however, that the incumbent prefers to offer only the old product.

**Proposition 3** *There exists a unique equilibrium in subgame  $\Gamma^B$ . In this equilibrium, the incumbent withdraws the new product entirely and sells only the old product for all  $\theta_1 > 0$ . The incumbent and the entrant set prices as in subgame  $\Gamma^E$ .*

Proposition 3 describes an intriguing result. When both firms introduce the new version of the durable good, the optimal response of the incumbent is to withdraw his new product from both the upgrade market and the new-purchase market.<sup>14</sup> The result can be explained as follows. If the incumbent remains in both markets, Bertrand price competition drives the new-purchase price and the upgrade price down to zero. As a consequence, the price for the old product is zero as well. Hence, each firm makes zero profits. It is obvious that the entrant cannot gain by exiting either market, since this would yield zero profits as well. In fact, staying in the market is a strictly dominant strategy for the entrant due to the small exit cost  $\varepsilon > 0$ . By contrast, the incumbent may want to avoid Bertrand price competition in the new-purchase market. Since the old product is directly competing against the new one, the incumbent has an incentive to withdraw the new product from the new-purchase market in order to generate positive profits from the old product. Moreover, we find that the incumbent can do even better by withdrawing the new product from the upgrade-market as well, and offering only the old product, as with history  $E$ . To understand this point, remember that for history  $E$  the entrant charges a uniform price in both markets since the incentive compatibility constraint  $p_U \leq p_H$  is always binding (Proposition 2). Therefore history  $E$  yields a higher price for the new product in the new-purchase market such that the demand for the old product will also be higher. The incumbent is therefore better-off avoiding Bertrand price competition in the upgrade-market, even though he will end up selling only the old product.

A similar result has been obtained by Judd (1985) for a multiproduct incumbent with horizontally differentiated goods who is threatened by an entrant. How robust is the result? As in Judd's model, product withdrawal by the incumbent monopolist is more likely to be the equilibrium outcome as the different product versions are better substitutes, as exits costs are low,

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<sup>14</sup>Notice that this result precludes a possible solution of the time inconsistency problem studied in Ausubel and Deneckere (1987) and Gul (1987). Ausubel and Deneckere (1987) show that a price-war upon entry can be used as a credible punishment strategy in an infinite horizon framework. This argument is not applicable to the case of entry via a new generation of the good, as in our paper. Since the monopolist has the old product which can generate a positive profit upon concession, such price-war equilibrium is not credible in our model.

and as the incumbent's costs to credibly destroy its own ability to produce the version that is not offered by the entrant are not too low. To see the last point, note that if the incumbent can commit to not produce the old product in our model the threat of intensive postentry competition may become credible. Such a commitment would implement a subgame  $\Gamma_B$  equilibrium with zero profits for both firms. While it is far from trivial to assess whether the incumbent would have an incentive to do so, we know that for certain parameter range the overall game would have multiple equilibria where one of them is the equilibrium that is unique in our setting. Moreover, in many cases the assumption that the incumbent cannot credibly destroy its ability to produce the old version appears to be the right one, especially when the firm acquires the ability to produce the new version of the good, as in our model.

It is interesting to note that Proposition 3 implies that innovation has no preemptive power in deterring entry, which stands in contrast to the debate between Gilbert and Newbery (1982) and Reinganum (1983). The difference is due to the possibility of earning profits on the old product after rival entry, together with the absence of any effective patent protection in our model.<sup>15</sup>

Finally, consumer leapfrogging in subgame  $\Gamma^B$  occurs under the same circumstances as in subgame  $\Gamma^E$ , which follows immediately from Proposition 3.

**Corollary 3** *Consumer leapfrogging occurs in  $\Gamma^B$  if  $x_1 < \theta_1 < x_2$ .*

## 4 First-period sales and innovation behavior

Given the above analysis of the second-period play, we will now solve for the subgame-perfect equilibrium of the entire game. There are two stages at which firms make decisions prior to the second-period sales: the pricing decision of the incumbent in the first period and the innovation investment decisions immediately before the second period.

Table 1 presents the payoff matrix at the time of the innovation decisions, given the costs  $K_I$  and  $K_E$  for the incumbent and the entrant, respectively. The incumbent is the row player and the entrant is the column player.  $\pi_j^h(\theta_1)$  denotes the second-period optimal profit accruing to firm  $j$  as a function of the first-period sales level  $\theta_1$ , where the subscript  $j = I, E$ , represents

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<sup>15</sup>Note that the result applies to product innovation in durable-goods as well as non-durable goods monopolies. Related is the work by Kamien and Schwartz (1978), who show in a dynamic setting that an incumbent monopolist will cease its R&D activities upon an entrant's innovation, when entry makes selling the old product more profitable than the new. Our analysis extends their argument to the decision about whether to cease sales of a new product which has already been introduced to the market.

the incumbent and the entrant, and the superscript  $h = N, I, E, B$ , represents the innovation history. Note that  $\pi_j^B(\theta_1) = \pi_j^E(\theta_1)$  for all  $\theta_1$  by Proposition 3.

	No Innovation	Innovation
No Innovation	$\pi_I^N(\theta_1), 0$	$\pi_I^E(\theta_1), \pi_E^E(\theta_1) - K_E$
Innovation	$\pi_I^I(\theta_1) - K_I, 0$	$\pi_I^E(\theta_1) - K_I, \pi_E^E(\theta_1) - K_E$

Table 1: Payoff Matrix for Second Period

Rolling back we can write the total profit of the incumbent as a function of  $\theta_1$ :

$$\Pi(\theta_1) = p_1(1 - \theta_1) + \pi_I^h(\theta_1) - K_I \mathcal{I}\{h = I, B\} \quad (20)$$

where  $p_1$  is the first-period price compatible with the marginal consumer of type  $\theta_1$ , and  $\mathcal{I}\{\cdot\}$  is an indicator function. The incumbent's optimal strategy at the beginning of the whole game can be specified as the choice of a first-period cutoff type  $\theta_1$  that maximizes  $\Pi(\theta_1)$ .

The subgame-perfect equilibrium of the entire game has different properties depending on whether entry takes place or not. We shall first analyze the equilibrium in which entry occurs and then turn to the equilibrium in which entry is prevented. As a preliminary step, we define  $\Lambda_{K_E} = \{\theta_1 \mid \pi_E^E(\theta_1) \leq K_E\}$ , namely the set of sales histories which yield a non-positive profit to the entrant when he innovates.<sup>16</sup> Notice that the incumbent can prevent entry by setting the first-period price in such a way that all consumers of type  $\theta \geq \theta_1 \in \Lambda_{K_E}$  purchase in the first period. We call  $\Lambda_{K_E}$  the no-entry set. The next lemma establishes useful properties of the no-entry set.

**Lemma 1** *1. If  $K_E < \frac{1}{4}s_\Delta$ , then  $\Lambda_{K_E} = \emptyset$ .*

*2. If  $K_E \geq \frac{1}{4}s_\Delta$ , then  $\Lambda_{K_E} = [0, \lambda_{K_E}] \neq \emptyset$ , where  $\lambda_{K_E} \geq x_1 > 0$ .*

The first part of the lemma implies that the no-entry set is empty, i.e. entry cannot be prevented, if the entrant's innovation cost is below a certain level. The second part reveals that the no-entry set is non-empty if the entrant's entry cost is high enough and that the upper

<sup>16</sup>We assume that the entrant stays out, i.e. chooses not to innovate, if the profit from entry is non-positive.

bound of the set is greater than or equal to  $x_1$  as defined in Proposition 2. This property has an important implication for the analysis of the equilibrium behavior when entry is prevented: it allows us to ignore the range of  $\theta_1$  smaller than  $x_1$ .

Consider now the equilibrium in which entry occurs. We know from Proposition 3 that the continuation game will be  $\Gamma^E$ , i.e. the incumbent will choose not to innovate and sell only the old product. The optimal first-period price, given entry, is hence the solution to the following maximization problem:

$$\max_{\{\theta_1\}} \Pi(\theta_1) = p_1(1 - \theta_1) + \pi_I^E(\theta_1). \quad (21)$$

We obtain the following result:

**Proposition 4** *If entry occurs in equilibrium, the incumbent chooses a first-period quantity of  $1 - \theta_1 = 1 - x_1$ .*

It is important to point out that  $(1 - x_1)$  is just the sales volume that will induce the entrant not to sell in the new-purchase market. By Proposition 2, any smaller quantity would admit competition in the new-purchase market, which would lower the second-period price for both, the new and the old product, and thus the incumbent's second-period profit. Once the entrant leaves the new-purchase market, larger first-period sales reduce the incumbent's profit through a lower first-period price as well as a lower second-period price, while the entrant's profit remains constant. Hence, the incumbent's profits are maximized by choosing the smallest sales volume that keeps the entrant out of the new-purchase market.<sup>17</sup>

Proposition 4 has an immediate consequence for the next result, which shows that the incumbent will always prevent entry, whenever there is the possibility to do so.

**Proposition 5** *Entry occurs in equilibrium if and only if  $K_E < \frac{1}{4}s_\Delta$ .*

The reasoning underlying the result is quite straightforward. If  $K_E < (1/4)s_\Delta$  such that  $\Lambda_{K_E}$  is empty, the incumbent has no choice but to concede and accommodate entry. To prove the reverse, consider  $K_E \geq (1/4)s_\Delta$  and suppose that the incumbent plans to accommodate

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<sup>17</sup>The negative impact of the first-period sales upon the entrant's second-period profits has been first identified by Bucovetsky and Chilton (1986) and Bulow (1986). Kühn and Padilla (1996) show that the effect persists in infinite horizon models even when the time between offers goes to zero. Carlton and Gertner (1989) exploit the same intuition to demonstrate that a durable-goods oligopolist has an incentive to sell rather than rent for strategic reasons.



entry. Proposition 4 implies that the incumbent's optimal decision for the first period is then to choose  $\theta_1 = x_1$ . However Lemma 1 (Statement 2) implies that  $\pi_E^E(x_1) < K_E$  so that the entrant cannot earn a positive profit from entry. Therefore entry does not take place. Hence entry is prevented almost by default, even if the incumbent plans to concede entry. The result indicates that the incumbent monopolist in a durable-good industry enjoys a substantial advantage in securing his monopoly position.

We proceed by characterizing the equilibrium in which there is no entry and the second-period subgame is either  $\Gamma^N$  or  $\Gamma^I$ , depending on the innovation decision of the incumbent. The incumbent's optimization problem is then given by

$$\max_{\{\theta_1, h=N, I\}} \Pi(\theta_1) = p_1(1 - \theta_1) + \pi_I^h(\theta_1) - K_I \mathcal{I}\{h = I\}, \quad (22)$$

subject to  $\theta_1 \in \Lambda_{K_E}$ .

The equilibrium outcome is described in the next proposition. According to Bain's terminology, we distinguish between *blockaded entry*, where the incumbent chooses a first-period price as if there were no entry threat but no entry occurs, and *deterred entry*, where entry cannot be blockaded but is prevented through limit pricing.

**Proposition 6** *Suppose  $K_E \geq (1/4) s_\Delta$ , so that no entry occurs in equilibrium. Then:*

1. *If  $[3s_L + s_\Delta] / [5s_L + s_\Delta] < \lambda_{K_E} \leq 1$ , entry is blockaded and the incumbent acts as in the absence of an entrant.*
2. *If  $3/5 \leq \lambda_{K_E} \leq [3s_L + s_\Delta] / [5s_L + s_\Delta]$ , entry is blockaded if the incumbent does not innovate, and deterred at  $\theta_1 = \lambda_{K_E}$  if the incumbent innovates.*
3. *If  $x_1 \leq \lambda_{K_E} \leq 3/5$ , the incumbent deters entry at  $\theta_1 = \lambda_{K_E}$ .*

The proposition distinguishes among three ranges for the upper bound of the no-entry set  $\lambda_{K_E}$ . Intuitively, for high  $\lambda_{K_E}$ , the entrant's innovation costs,  $K_E$ , are so high that entry is prevented, even if the incumbent acts as if there were no entry threat. For intermediate  $\lambda_{K_E}$ , the incumbent can choose to deter entry by producing at the boundary of the no-entry set. The proposition indicates that the optimal decision depends on the innovation cost of the incumbent. The reason is that consumers anticipate the introduction of a new generation in the second-period for low enough innovation costs,  $K_I$ . They have then a high incentive to postpone the

initial purchase. This, in turn, can make entry, *ceteris paribus*, profitable. Hence, to prevent entry in the case of low innovation cost,  $K_I$ , the incumbent must set the first-period price lower than if there were no entry threat. That is, the incumbent must engage in limit pricing. Finally, for low  $\lambda_{K_E}$ , the entrant's innovation cost,  $K_E$ , is so low that the incumbent will always engage in limit pricing to deter entry, irrespective of his own innovation costs.

Proposition 6 reveals that the concept of limit pricing due to Bain (1949) is valid in durable-goods industries. As is well known, an argument which essentially amounts to the requirement of subgame perfection makes the limit-pricing strategy ineffective in non-durable-goods industries. The key aspect of Proposition 6 is that the second-period demand function is determined by the first-period sales volume. By contrast, it is independent of the first-period sales in the case of non-durable goods.

Note that the practice of limit pricing only implies that the price which deters entry is lower compared to the price under no threat of entry. Since the monopolist would flood the first-period market even when entry cannot be deterred (Proposition 4), the price under entry may be even lower than the price under entry deterrence. Hence care seems to be called for when assessing any practical pricing policy in view of its effect on entry deterrence.

We conclude this section by checking whether consumer leapfrogging is possible in the overall game.

**Corollary 4** *Consumer leapfrogging occurs in the entry-deterrence equilibrium with innovation for  $x_1 < \lambda_{K_E} < 1/2$ .*

For a durable-goods monopoly without entry threat, Fudenberg and Tirole (1998) demonstrate that consumer leapfrogging only occurs when production is costly. By contrast, our model predicts the possibility of leapfrogging in the case of costless production. The intuition behind our result is that entry deterrence by limit pricing induces some consumers to purchase in period 1 whose valuations are not high enough to warrant an upgrade in period 2. On the other hand, the even larger first-period sales volume chosen in the equilibrium in which entry takes place does not imply consumer leapfrogging, because the valuation of the consumers who have not purchased in period 1 is so low that the entrant finds it optimal to serve only the consumers in the upgrade market. These two observations suggest that the occurrence of leapfrogging can also be attributed to the competitive pressure under entry threat.

## 5 Welfare analysis of innovation investments

The threat of entry via a new generation of the durable good has a few straightforward effects on social welfare. First, the practice of limit pricing allows more consumers to consume the durable good compared to the situation without entry threat. Second, an even higher sales volume is obtained when entry is accommodated. However, even the equilibrium which involves entry entails a loss of efficiency against the first best in which both products are provided at prices equal to the marginal cost of zero.

In this section we focus on the non-trivial question, albeit of partial nature, of whether the durable-goods monopolist and the potential entrant have proper incentives to invest in innovation.<sup>18</sup> We first show that when innovation occurs in equilibrium, inefficiency in innovation can be caused by either firm: the incumbent may innovate even though innovation by the entrant is more efficient, i.e.  $K_E < K_I$ , while the entrant may innovate even if though innovation by the incumbent is more efficient, i.e.  $K_I < K_E$ . To understand this, note that the possibility of entry deterrence depends only on the entrant's innovation costs and profits, and not on the incumbent's innovation costs. When the incumbent successfully deters entry, he may invest in innovation, although the entrant has a cost advantage. On the other hand, the inefficiency can occur in the opposite way as well. If the no-entry set is empty, the incumbent is forced to accommodate entry. But, as shown above, the incumbent then never innovates, irrespective of his innovation costs.

**Proposition 7** *Suppose that innovation occurs in the equilibrium.*

1. *When  $K_E \geq \frac{1}{4}s_\Delta$  so that no entry occurs in equilibrium, the incumbent may innovate even if  $K_E < K_I$ .*
2. *When  $K_E < \frac{1}{4}s_\Delta$  so that entry occurs in equilibrium, the entrant may innovate even if  $K_I < K_E$ .*

Proposition 7 reveals two potential inefficiencies when innovation occurs. We turn next to the case when no firm innovates, and show that the monopolist's practice of limit pricing always results in a rate of technological progress that is lower than the socially optimal level.

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<sup>18</sup>The question lies at the center of the recent trial on Microsoft (see, for instance, the *Washington Post*, November 30, 1999, p. A29), although it is admittedly of a more limited scope here. Our approach highlights the most controversial issue in the trial.

If entry via a new generation of the durable good occurs, social welfare is given by

$$\begin{aligned}
W^E &= 2 \int_{x_1}^1 s_L \theta \, d\theta + \int_{\frac{1}{2}}^1 s_\Delta \theta \, d\theta + \int_{\frac{1}{2}x_1}^{x_1} s_L \theta \, d\theta - K_E \\
&= s_L \left(1 - \frac{5}{8}x_1^2\right) + \frac{3}{8}s_\Delta - K_E
\end{aligned} \tag{23}$$

which follows from Propositions 2 and 4. If, on the other hand, entry is deterred and no innovation takes place, social welfare is given by

$$\begin{aligned}
W^N &= 2 \int_{\lambda_{K_E}}^1 s_L \theta \, d\theta + \int_{\frac{1}{2}\lambda_{K_E}}^{\lambda_{K_E}} s_L \theta \, d\theta \\
&= s_L \left(1 - \frac{5}{8}\lambda_{K_E}^2\right)
\end{aligned} \tag{24}$$

which follows from the analysis in Section 3.1 and Proposition 6.

For entry to be welfare enhancing, the efficiency gains from the entrant's innovation must be large enough to offset the entrant's innovation costs,  $K_E$ . By comparing (23) and (24), we are able to show the following proposition.

**Proposition 8** *In the entry-deterrence equilibrium without innovation, the social benefits from the entrant's innovation always exceed the entrant's innovation costs: The equilibrium is characterized by underinvestment in innovation.*

The intuition behind the proposition is that entry deterrence by limit pricing induces an inefficiency which increases as the entrant's innovation cost,  $K_E$ , rise, since the first-period sales volume necessary for entry deterrence is decreasing in  $K_E$ . For low  $K_E$ , the efficiency loss due to entry deterrence is minimal, however the welfare gains from the consumption of the new durable good offered by the entrant easily dominate the entrant's innovation cost. For moderate  $K_E$ , we find that the allocative losses due the reduction of the first-period sales volume are large enough to make the entrant's innovation always welfare-increasing. Finally, for high innovation cost,  $K_E$ , entry is blockaded and not deterred.

Proposition 8 indicates that the practice of entry deterrence may lead to less innovation than socially optimal. The result provides a rationale for possible government intervention in encouraging innovation by a potential entrant. Furthermore, the proposition has an interesting

implication for the recent U.S. v. Microsoft trial, in which Microsoft consistently argued that it faces the correct innovation incentive because of the time-inconsistency problem in durable-goods industries: Once the old generation of the durable is sold, the firm must innovate to generate further revenues. A careful examination of the argument reveals that this is an unwarranted extrapolation of the Coasian argument to the case in which a potential entrant threatens to innovate as well. Indeed the analysis in this section suggests that their claim is not true in general.

## 6 Conclusion

We find that the durability of the good either acts as an entry barrier itself or creates an opportunity for the incumbent firm to deter entry by limit pricing. Although the power to deter entry is not equivalent to the lack of incentive to innovate, it allows the incumbent to generate underinvestment in innovation or make an inefficient innovation decision. It is rather surprising that the inefficiency in innovation may go in the opposite direction as well, namely that the entrant may innovate even though the incumbent has a cost advantage in innovation.

Our analysis can account for the apparent puzzle of Microsoft's low pricing of its Windows software. But other explanations, such as network effects, may also account for this observation. How much of the low price is due to network externalities or to product durability remains an open question. The analysis also suggests that there is a tendency for a single, persistent technological leader in durable-goods monopolies, which appears compatible with a few outstanding cases in the computer industry: Microsoft in the market for operating systems, Intel in the computer central processing units (CPU) market, and Cisco in the network equipment market.

Our results may have implications for empirical studies on innovation and entry dynamics as well as antitrust policies. In particular, we show that Microsoft's claim of the competitiveness of the durable-goods industry does not necessarily imply innovation efficiency since the intertemporal linkage which causes the problem of time inconsistency also endows an incumbent monopolist with the power to deter entry. This power in turn may cause inefficiency in innovation investments.

Finally, we would like to emphasize that the issue of dynamic competition considered here could be crucial for issues of economic growth since durable goods are often used as factors

of production. Hence, results which draw on a careful analysis of entry deterrence in durable-goods monopoly may provide important implications for policies on growth.

## Appendix

**Proof.** (Proposition 1)

Define  $z_2 \equiv s_\Delta / [s_L + s_\Delta]$ . From the analysis in Section 3.1, we know that the incumbent will price discriminate if  $\theta_1 > z_2$  (statement 1 of Proposition 1). Consider next the range of  $\theta_1$  in which (6) is binding, i.e.  $\theta_1 \leq z_2$ . The incumbent may charge a uniform price for the new product in both markets or offer it only in one market. In serving both markets, there are in turn three options: (i) either the pricing ensures that the first-period cutoff type  $\theta_1$  strictly prefers to upgrade, or (ii) is indifferent between upgrading and not, or (iii) strictly prefers not to upgrade. To determine the optimal sales policy, we will first consider the different options in turn and compare the resulting profit values.

Under option (i), optimal uniform pricing is the solution of

$$\max_{\{p_U, p_H\}} \left(1 - \frac{p_H}{s_L + s_\Delta}\right) p_H \quad (25)$$

subject to

$$\theta_1 > \frac{p_U}{s_\Delta} \quad (26)$$

$$\frac{p_H}{s_L + s_\Delta} \leq \theta_1 \quad (27)$$

$$p_U = p_H \quad (28)$$

which yields

$$p_H = p_U = \frac{1}{2}(s_L + s_\Delta). \quad (29)$$

Checking the constraints reveals that the relevant range of  $\theta_1$  for option (i) coincides with the range in which the incumbent finds it optimal to price discriminate with respect to purchase history. Hence, option (i) is always dominated.

Under option (ii), the incumbent solves

$$\max_{\{p_U, p_H\}} \left[ \left(1 - \frac{p_U}{s_\Delta}\right) p_U + \left(\theta_1 - \frac{p_H}{s_L + s_\Delta}\right) p_H \right] \quad (30)$$

subject to

$$\frac{p_U}{s_\Delta} \geq \theta_1 \quad (31)$$

$$\frac{p_H}{s_L + s_\Delta} \leq \theta_1 \quad (32)$$

$$p_U = p_H \quad (33)$$

Notice that under option (iii), the maximization problem differs from (ii) only in that constraint (31) must hold with a strict inequality. Hence, maximizing (30) subject to (33), we obtain for both options that

$$p_H = p_U = \frac{1}{2} s_\Delta \frac{s_L + s_\Delta}{s_L + 2s_\Delta} (1 + \theta_1). \quad (34)$$

Taking the other constraints into account, we obtain the relevant ranges for options (ii) and (iii) as  $\theta_1 \leq z_2$  and  $s_\Delta / [2s_L + 3s_\Delta] \leq \theta_1 \leq z_2$ , respectively. An inspection of the implied profits reveals that option (iii) yields strictly greater profits than option (ii) in the relevant range.

To complete the proof, we determine the profits obtainable from foregoing sales of the new product in one of the markets. In particular, the incumbent can choose to offer the new product only to consumers in the upgrade market and continue to sell the old product to the consumers in the new-purchase market. The optimal upgrade price is then given by (8) while the optimal old-product price is obtained as the solution to (1). By comparing the profits obtainable with this policy and options (ii) and (iii), it is easy to verify that there is a unique value

$$z_1 \equiv \frac{s_\Delta (s_L + s_\Delta - \sqrt{s_\Delta} \sqrt{(s_L + 2s_\Delta)})}{s_\Delta s_L + s_L^2 - s_\Delta^2}$$

with  $s_\Delta / [2s_L + 3s_\Delta] < z_1 < z_2$ , such that the incumbent prefers to sell the new product in both markets at a uniform price if  $z_1 < \theta_1 \leq z_2$  (statement 2), and prefers to offer the new product only in the upgrade market along with the old product in the new-purchase market if  $0 \leq \theta_1 \leq z_1$  (statement 3). ■

**Proof.** (Corollary 1)

We will analyze each of the ranges of  $\theta_1$  that are specified in statements 1-3 of Proposition 1 for  $\Gamma^I$ , and check whether leapfrogging occurs. First, for  $1/2 \leq \theta_1 \leq 1$ , the incumbent serves the whole upgrade market, which precludes leapfrogging. Second, for  $z_2 < \theta_1 < 1/2$ , the



incumbent's optimal prices in the second period are given in Table 2. We obtain that  $p_U/s_\Delta > \theta_1$  if  $\theta_1 < 1/2$ , and  $p_H/[s_L + s_\Delta] < \theta_1$  if  $\theta_1 > 0$ . That is, the marginal consumer who upgrades in the second period is of a type that is strictly higher than  $\theta_1$ , and the new product is bought by consumers of type below  $\theta_1$ , i.e. leapfrogging occurs. Third, for  $z_1 < \theta_1 \leq z_2$ , the incumbent sells the new product at the optimal uniform price given in Table 2. Then  $p_H/s_\Delta > \theta_1$  if  $\theta_1 < [s_L + s_\Delta]/[s_L + 3s_\Delta]$ , which holds for all  $\theta_1 < z_2$ . And,  $p_H/[s_L + s_\Delta] < \theta_1$  if  $\theta_1 > s_\Delta/[2s_L + 3s_\Delta]$ , which holds for all  $\theta_1 > z_1$ , i.e. leapfrogging occurs. Finally, for  $0 \leq z_1 \leq \theta_1$ , the new product is sold in the upgrade market only, which precludes leapfrogging. ■

**Proof.** (Proposition 2)

From the analysis in Section 3.2 we know that the entrant will never charge a cross-upgrade discount in  $\Gamma^E$ . The entrant will either charge a uniform price in both markets or offer the new product only in one market. As in  $\Gamma^I$ , there are in turn three options in serving both markets: (i) either the pricing ensures that the first-period cutoff type  $\theta_1$  strictly prefers to upgrade, or (ii) is indifferent between upgrading and not, or (iii) strictly prefers not to upgrade. The analyses of the three cases are similar to those for Proposition 1 and omitted. In subgame  $\Gamma^E$  the critical values of  $\theta_1$  are:

$$\begin{aligned} x_1 &= \frac{(7\sqrt{2} - 8)s_L + (8\sqrt{2} - 8)s_\Delta}{8s_L + 8s_\Delta} \\ x_2 &= \frac{2s_L + 2s_\Delta}{5s_L + 6s_\Delta} \\ x_3 &= \frac{2s_L + 2s_\Delta}{3s_L + 4s_\Delta} \end{aligned}$$

with  $0 < x_1 < x_2 < 1/2 < x_3$ . The proof of statement 4 is straightforward and omitted as well. ■

**Proof.** (Corollary 2)

We will analyze each of the ranges of  $\theta_1$  that are specified in Proposition 2 for  $\Gamma^E$  and check whether leapfrogging occurs. First, for  $x_3 < \theta_1 \leq 1$ , the entrant charges a uniform price such that the cutoff type  $\theta_1$  prefers to buy. In addition, the entrant sells the new product in the new-purchase market, i.e. no leapfrogging occurs. Second, for  $x_2 \leq \theta_1 \leq x_3$ , the argument is the same as for  $x_3 < \theta_1 \leq 1$ . Third, for  $x_1 < \theta_1 < x_2$ , the equilibrium prices are given in Table 2. It is easy to show that  $p_H/s_\Delta > \theta_1$  if  $\theta_1 < x_2$ , and  $[p_H - p_L]/s_\Delta < \theta_1$  if  $\theta_1 > [s_L + 2s_\Delta]/[6s_L + 6s_\Delta] < x_1$ , i.e. leapfrogging occurs if  $\theta_1 < x_2$ . Finally, for

$0 \leq \theta_1 \leq x_1$ , the new product is not sold to consumers in the new-purchase market, which prevents leapfrogging. ■

**Proof.** (Proposition 3)

Consider the incumbent's strategy of selling both products. The incumbent has three alternative sales strategies for the new product. First, selling the new product in both, the upgrade market and the new-purchase market. Second, selling the new product only in the new-purchase market. And third, selling the new product only in the upgrade market. Among these sales strategies, the first two yield zero profit to the incumbent, since Bertrand competition reduces the price of the new product as well as the price of the old product to 0. The third strategy of offering the new product only in the upgrade market reduces the upgrade price to 0. This strategy effectively produces the market structure of vertical product differentiation in the new-purchase market, with the entrant as is the high-quality firm and the incumbent as the low-quality firm.

However, the incumbent can gain by withdrawing the new product entirely. It is easy to verify that the incumbent's profit obtained in the case of the history  $E$ , in which only the entrant sells the new product and the incumbent continues to sell the old version, strictly exceeds the profit obtainable with history  $B$  and free upgrading for all  $\theta_1 < 1$ , and is the same for  $\theta_1 = 1$ . While staying in the market is a strictly dominant strategy for the entrant in any continuation equilibrium due to the small but positive exit cost  $\varepsilon > 0$ , the incumbent is strictly better off withdrawing the new product. ■

**Proof.** (Lemma 1)

From Proposition 2 we know that  $\pi_E^E(\theta_1)$  is monotone increasing in  $\theta_1$  and bounded from below by  $(1/4) s_\Delta$ . It follows that  $\pi_E^E(\theta_1) \leq K_E$  only if  $K_E \geq (1/4) s_\Delta$ , i.e. the first part of the lemma.

To prove the second part, notice that  $\pi_E^E(\theta_1) \leq \pi_E^E(\lambda_{K_E}) \leq K_E$  for all  $\theta_1 \leq \lambda_{K_E}$  by the monotonicity of  $\pi_E^E(\theta_1)$  and the definition of  $\lambda_{K_E}$ . For  $\theta_1 \leq x_1$ ,  $\pi_E^E(\theta_1)$  is constant at  $(1/4) s_\Delta$  so for  $K_E \geq (1/4) s_\Delta$  there exists  $\lambda_{K_E} \geq x_1$  such that  $\pi_E^E(\lambda_{K_E}) = K_E$ . ■

**Proof.** (Proposition 4)

To find the optimal first-period choice of the incumbent when entry occurs in equilibrium, we will proceed in the following way: (i) First, we compute the first-period demand function in terms of the first-period cutoff type  $\theta_1$ , given entry in the second period. Using Proposition 2, we obtain four ranges of  $\theta_1$  with different first-period demand and profit functions. (ii) Second,

we determine the optimum in each of the four ranges separately. (iii) Finally, we compare the associated profits across different ranges, and select the one which yields the highest total profit.

(i) Given that  $0 \leq \theta_1 \leq x_1$ , the  $\theta_1$ -type is given  $2s_L\theta_1 - p_1 = s_L\theta_1 - p_L \Leftrightarrow p_1 = 3s_L\theta_1/2$ .

Given  $x_1 < \theta_1 < x_2$ , the  $\theta_1$ -type is given by  $2s_L\theta_1 - p_1 = (s_L + s_\Delta)\theta_1 - p_H \Leftrightarrow p_1 = (s_L - s_\Delta)\theta_1 + [2s_\Delta(s_L + s_\Delta)] / [(7s_L + 8s_\Delta)(1 + \theta_1)]$ .

Given  $x_2 \leq \theta_1 \leq x_3$ , the  $\theta_1$ -type is given by  $2s_L\theta_1 - p_1 = (s_L + s_\Delta)\theta_1 - p_H \Leftrightarrow p_1 = s_L\theta_1$  or  $s_L\theta_1 - p_1 + (s_L + s_\Delta)\theta_1 - p_H = (s_L + s_\Delta)\theta_1 - p_H \Leftrightarrow p_1 = s_L\theta_1$ .

Given  $x_3 < \theta_1 \leq 1$ , the  $\theta_1$ -type is given by  $s_L\theta_1 - p_1 + (s_L + s_\Delta)\theta_1 - p_H = (s_L + s_\Delta)\theta_1 - p_H \Leftrightarrow p_1 = s_L\theta_1$ .

(ii) The next step is to determine the optimum of  $\Pi(\theta_1)$  in each of the four ranges. It is easy to verify that, for  $0 \leq \theta_1 \leq x_1$ ,  $\Pi(\theta_1)$  attains its optimum at  $\theta_1 = x_1$ . For  $x_1 < \theta_1 < x_2$ , the optimum of  $\Pi(\theta_1)$  lies at the lower boundary for high values of  $s_\Delta/s_L$ , and at the higher boundary for low values of  $s_\Delta/s_L$ , and in-between for medium values of  $s_\Delta/s_L$ . For  $x_2 \leq \theta_1 \leq x_3$  and  $x_3 < \theta_1 \leq 1$ ,  $\Pi(\theta_1)$  attains its optimum at  $\theta_1 = x_3$ .

(iii) Comparing the associated profits across ranges yields  $\theta_1 = x_1$  as the optimal first-period choice. ■

**Proof.** (Proposition 6)

Suppose that  $K_E \geq (1/4)s_\Delta$  such that  $\Lambda_{K_E}$  is non-empty. To prove the proposition we will first consider the case in which the incumbent does not innovate and then turn to the case in which the incumbent innovates.

Without innovation the incumbent's problem is to maximize

$$\Pi(\theta_1) = p_1(1 - \theta_1) + \pi_I^N(\theta_1) \quad (35)$$

subject to  $\theta_1 \in \Lambda_{K_E}$ .

When the no-entry constraint is not binding, the incumbent's problem reduces to the standard maximization problem of a durable-goods monopolist, which is solved, for instance, by Bulow (1982). That is,  $\theta_1 = 3/5$ .

The no-entry constraint is binding, however, for  $\lambda_{K_E} \leq 3/5$ . That is, the incumbent is constrained to supply at least  $\lambda_{K_E}$  to prevent entry. To find the respective optimal first-period price, we need to derive the first-period demand. That is, we need to determine, for any price  $p_1$ , the  $\theta_1$ -type consumer who is indifferent between buying the durable good in period 1 for

$p_1$  or not. The concavity of the total profit function implies that the optimal quantity is exactly  $\lambda_{K_E}$ .

Next, in the case of innovation the incumbent maximizes

$$\Pi(\theta_1) = p_1(1 - \theta_1) + \pi_I^I(\theta_1) - K_I \quad (36)$$

subject to  $\theta_1 \in \Lambda_{K_E}$ .

Suppose first that the no-entry constraint is not binding. To find the optimal first-period choice of the incumbent in the case of no entry, we proceed in a similar way as in the proof of Proposition 4: (i) First, we derive the first-period demand function in terms of the first-period cutoff type  $\theta_1$ , given no entry in the second period. Using Proposition 1, we obtain different first-period demand and profit functions for four ranges of  $\theta_1$ . (ii) Second, we determine the optimum in each of the four ranges separately. (iii) Finally, we compare the associated profits across different ranges, and select the one which yields the highest total profit.

(i) Given that  $0 \leq \theta_1 \leq z_1$ , the  $\theta_1$ -type is given by  $2s_L\theta_1 - p_1 = s_L\theta_1 - p_L \Leftrightarrow p_1 = 3s_L\theta_1/2$ .

Given that  $z_1 < \theta_1 \leq z_2$ , the  $\theta_1$ -type is given by  $2s_L\theta_1 - p_1 = (s_L + s_\Delta)\theta_1 - p_H \Leftrightarrow p_1 = \theta_1(s_L - s_\Delta) + [s_\Delta(s_L + s_\Delta)/2] / [(s_L + 2s_\Delta)(1 + \theta_1)]$ .

Given that  $z_2 \leq \theta_1 \leq 1/2$ , the  $\theta_1$ -type is given by  $2s_L\theta_1 - p_1 = (s_L + s_\Delta)\theta_1 - p_H \Leftrightarrow p_1 = \theta_1(3s_L - s_\Delta)/2$ .

Given that  $1/2 < \theta_1 \leq 1$ , the  $\theta_1$ -type is given by  $s_L\theta_1 - p_1 + (s_L + s_\Delta)\theta_1 - p_U = (s_L + s_\Delta)\theta_1 - p_H \Leftrightarrow p_1 = \theta_1(3s_L - s_\Delta)/2$ .

(ii) The next step is to determine the optimum of  $\Pi(\theta_1)$  in each of the four ranges. It is easy to verify that, for  $0 \leq \theta_1 \leq z_1$ , and  $z_1 < \theta_1 \leq z_2$  and  $z_2 < \theta_1 \leq 1/2$ ,  $\Pi(\theta_1)$  attains its optimum at the upper boundary of the respective range of  $\theta_1$ , respectively. For  $1/2 \leq \theta_1 \leq 1$ , the optimum of  $\Pi(\theta_1)$  lies at  $\theta_1 = [3s_L + s_\Delta] / [5s_L + s_\Delta]$ .

(iii) By the continuity of  $\Pi(\theta_1)$ , it follows immediately from (ii) that  $\theta_1 = [3s_L + s_\Delta] / [5s_L + s_\Delta]$  is the optimal first-period choice given no entry threat.

To complete the proof, observe that the incumbent is constrained by the no-entry set when  $\lambda_{K_E} \leq [3s_L + s_\Delta] / [5s_L + s_\Delta]$ . The concavity of the total profit function implies that the optimal first period sales is obtained at the boundary,  $\lambda_{K_E}$ . To get the optimal first-period price we substitute  $\lambda_{K_E}$  for  $\theta_1$  in the first-period demand obtained in step (i).

Collecting these points yields the proposition as stated. ■

**Proof.** (Corollary 4)

There is no possibility of leapfrogging in  $\Gamma^N$ , since there is only one generation of the durable good. By Corollary 1, leapfrogging occurs in  $\Gamma^I$  for  $z_1 < \theta_1 < 1/2$ . Since  $x_1$  is greater than  $z_1$ , leapfrogging occurs in the no-entry equilibrium with innovation for  $x_1 < \theta_1 < 1/2$ . Finally, leapfrogging does not occur in the equilibrium with entry. To see this note that, by Corollary 2, leapfrogging in  $\Gamma^E$  would require that  $x_1 < \theta_1 < x_2$  is satisfied. However, the optimal first period sales quantity in the entry equilibrium is  $x_1$ . ■

**Proof.** (Proposition 7)

Suppose that  $K_E \geq (1/4)s_\Delta$  such that  $\Lambda_{K_E}$  is non-empty. Proposition 5 implies that the incumbent will not accommodate entry in equilibrium. The incumbent chooses a  $\theta_1$  greater than or equal to  $x_1$  such that  $\pi_E^E(\theta_1) = K_E$  (see Proposition 6).

Note that  $\pi_I^I(\theta_1)$  does not depend on  $K_E$ , and the incumbent chooses to innovate only if  $\pi_I^I(\theta_1) - \pi_I^N(\theta_1) \geq K_I$ . Hence, to prove the proposition, it suffices to show that  $\pi_I^I(\theta_1) - \pi_I^N(\theta_1) > \pi_E^E(\theta_1)$  is possible for some values of  $s_\Delta$  and  $s_L$ . Suppose that the difference between  $s_L$  and  $s_\Delta$  is very small. In that case  $z_1 < x_1 < x_2 < z_2 < 1/2$ , and we have  $\pi_I^I(\theta_1) - \pi_I^N(\theta_1) > \pi_E^E(\theta_1)$  for  $x_1 \leq \theta_1 < z_2$ .

To show the second statement of the proposition, suppose that  $K_E < (1/4)s_\Delta$  and  $K_I < K_E$ . In this case the incumbent accommodates entry in equilibrium, since the no-entry set is empty. Therefore the entrant innovates even if the incumbent has a lower innovation cost. ■

**Proof.** (Proposition 8)

The equilibrium in which the entrant innovates is more efficient than the entry-deterrence equilibrium without innovation if  $W^E$  (given by (23)) dominates  $W^N$  (given by (24)) for a given  $K_E$ . We obtain that  $W^E$  dominates  $W^N$  if

$$\frac{5}{8}s_L(\lambda_{K_E}^2 - x_1^2) + \frac{3}{8}s_\Delta - K_E \geq 0. \quad (37)$$

Hence it remains to show that  $W^E$  is greater than  $W^N$  whenever  $K_E$  is consistent with  $\lambda_{K_E}$ .

Recall that  $\lambda_{K_E}$  is the first period sales when the entrant makes zero profit from entry.

Proposition 2 implies that  $K_E$  and  $\lambda_{K_E}$  are related as follows for 3 ranges:

$$K_E = \begin{cases} 4s_\Delta \frac{(s_L+s_\Delta)^2}{(3s_L+4s_\Delta)^2} & \text{if } x_3 < \lambda_{K_E} \leq \frac{3}{5} \\ s_\Delta \theta_1 - \frac{1}{2} s_\Delta \frac{s_L+2s_\Delta}{s_L+s_\Delta} \theta_1^2 & \text{if } x_2 \leq \lambda_{K_E} \leq x_3 \\ 8s_\Delta \frac{(s_L+s_\Delta)^2}{(7s_L+8s_\Delta)^2} (1 + \theta_1)^2 & \text{if } x_1 \leq \lambda_{K_E} \leq x_2 \end{cases} \quad (38)$$

Substituting  $K_E$  into (37) and evaluating it for different range of  $\lambda_{K_E}$ , we can easily confirm that  $W^E$  dominates  $W^N$  for all ranges. The proof is complete. ■

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	$\theta_1$	$p_L$	$p_H$	$p_U$	$\theta_L$	$\theta_H$	$\theta_U$
$\Gamma^N$	-	$\frac{1}{2}s_L\theta_1$	-	-	$\frac{1}{2}\theta_1$	-	-
	$(\frac{1}{2}, 1]$	-	$\frac{1}{2}(s_L + s_\Delta)\theta_1$	$s_\Delta\theta_1$	-	$\frac{1}{2}\theta_1$	$\theta_1$
$\Gamma^I$	$(z_2, \frac{1}{2}]$	-	$\frac{1}{2}(s_L + s_\Delta)\theta_1$	$\frac{1}{2}s_\Delta$	-	$\frac{1}{2}\theta_1$	$\frac{1}{2}$
	$(z_1, z_2]$	-	$\frac{s_\Delta(s_L + s_\Delta)}{2(s_L + 2s_\Delta)}(1 + \theta_1)$	$\frac{s_\Delta(s_L + s_\Delta)}{2(s_L + 2s_\Delta)}(1 + \theta_1)$	-	$\frac{s_\Delta}{2(s_L + 2s_\Delta)}(1 + \theta_1)$	$\frac{s_L + s_\Delta}{2(s_L + 2s_\Delta)}(1 + \theta_1)$
$\Gamma^E$	$[0, z_1]$	$\frac{1}{2}s_L\theta_1$	-	$\frac{1}{2}s_\Delta$	$\frac{1}{2}\theta_1$	-	$\frac{1}{2}$
	$(x_3, 1]$	$\frac{s_\Delta s_L}{3s_L + 4s_\Delta}$	$\frac{2s_\Delta(s_L + s_\Delta)}{3s_L + 4s_\Delta}$	$\frac{2s_\Delta(s_L + s_\Delta)}{3s_L + 4s_\Delta}$	$\frac{s_L}{3s_L + 4s_\Delta}$	$\frac{2s_\Delta}{3s_L + 4s_\Delta}$	$\frac{2(s_L + s_\Delta)}{3s_L + 4s_\Delta}$
	$(x_2, x_3]$	$\frac{s_\Delta s_L}{2(s_L + s_\Delta)}\theta_1$	$s_\Delta\theta_1$	$s_\Delta\theta_1$	$\frac{s_\Delta}{2(s_L + s_\Delta)}\theta_1$	$\frac{s_\Delta}{(s_L + s_\Delta)}\theta_1$	$\theta_1$
	$(x_1, x_2]$	$\frac{s_\Delta s_L}{7s_L + 8s_\Delta}(1 + \theta_1)$	$\frac{2s_\Delta(s_L + s_\Delta)}{2(7s_L + 8s_\Delta)}(1 + \theta_1)$	$\frac{2s_\Delta(s_L + s_\Delta)}{2(7s_L + 8s_\Delta)}(1 + \theta_1)$	$\frac{s_\Delta}{7s_L + 8s_\Delta}(1 + \theta_1)$	$\frac{2s_\Delta}{2(7s_L + 8s_\Delta)}(1 + \theta_1)$	$\frac{2(s_L + s_\Delta)}{2(7s_L + 8s_\Delta)}(1 + \theta_1)$
	$[0, x_1]$	$\frac{1}{2}s_L\theta_1$	-	$\frac{1}{2}s_\Delta$	$\frac{1}{2}\theta_1$	-	$\frac{1}{2}$

Table 2: Equilibrium Strategy for Second Period Subgames

	$\theta_1$	$\pi_I$	$\pi_E$
$\Gamma^N$	-	$\frac{1}{4}s_L\theta_1^2$	-
	$(\frac{1}{2}, 1]$	$(1 - \theta_1)\theta_1 s_\Delta + \frac{1}{4}(s_\Delta + s_L)\theta_1^2$	-
$\Gamma^I$	$(z_2, \frac{1}{2}]$	$\frac{1}{4}s_\Delta + \frac{1}{4}(s_L + s_\Delta)\theta_1^2$	-
	$(z_1, z_2]$	$\frac{1}{4}s_\Delta \frac{s_L + s_\Delta}{s_L + 2s_\Delta}(1 + \theta_1)^2$	-
$\Gamma^E$	$[0, z_1]$	$\frac{1}{4}s_\Delta + \frac{1}{4}s_L\theta_1^2$	-
	$(x_3, 1]$	$\frac{s_L s_\Delta (s_L + s_\Delta)}{(3s_L + 4s_\Delta)^2}$	$4s_\Delta \frac{(s_L + s_\Delta)^2}{(3s_L + 4s_\Delta)^2}$
	$(x_2, x_3]$	$\frac{s_L s_\Delta}{4(s_L + s_\Delta)}\theta_1^2$	$s_\Delta\theta_1 - \frac{1}{2}s_\Delta \frac{s_L + 2s_\Delta}{s_L + s_\Delta}\theta_1^2$
	$(x_1, x_2]$	$\frac{s_L s_\Delta (s_L + s_\Delta)}{(7s_L + 8s_\Delta)^2}(1 + \theta_1)^2$	$8s_\Delta \frac{(s_L + s_\Delta)^2}{(7s_L + 8s_\Delta)^2}(1 + \theta_1)^2$
	$[0, x_1]$	$\frac{1}{4}s_L\theta_1^2$	$\frac{1}{4}s_\Delta$

Table 3: Equilibrium profit for Second Period Subgames

	$\lambda_{K_E}$	$p_1$	$\theta_1$	$\Pi$
$\Gamma^N$	$(\frac{3}{5}, 1]$	$\frac{9}{10}$	$\frac{3}{5}$	$\frac{9}{20}s_L$
	$(x_1, \frac{3}{5}]$	$\frac{3}{2}s_L\lambda_{K_E}$	$\lambda_{K_E}$	$\frac{3}{2}s_L\lambda_{K_E} - \frac{5}{4}s_L\lambda_{K_E}^2$
$\Gamma^I$	$(\frac{3s_L+s_\Delta}{5s_L+s_\Delta}, 1]$	$\frac{9s_L^2-s_\Delta^2}{2(5s_L+s_\Delta)}$	$\frac{3s_L+s_\Delta}{5s_L+s_\Delta}$	$\frac{(3s_L+s_\Delta)^2}{4(5s_L+s_\Delta)}$
	$(\frac{1}{2}, \frac{3s_L+s_\Delta}{5s_L+s_\Delta}]$	$\frac{1}{2}(3s_L-s_\Delta)\lambda_{K_E}$	$\lambda_{K_E}$	$\frac{1}{2}(3s_L+s_\Delta)\lambda_{K_E} - \frac{1}{4}(5s_L+s_\Delta)\lambda_{K_E}^2 - K_I$
	$(z_2, \frac{1}{2}]$	$\frac{1}{2}(3s_L+s_\Delta)\lambda_{K_E} - \frac{1}{2}s_\Delta$	$\lambda_{K_E}$	$-\frac{1}{4}s_\Delta + \frac{1}{2}(3s_L+2s_\Delta)\lambda_{K_E} - \frac{1}{4}(5s_L+s_\Delta)\lambda_{K_E}^2 - K_I$
	$(x_1, z_2]$	$s_L\lambda_{K_E}$	$\lambda_{K_E}$	$\frac{s_\Delta(s_L+s_\Delta)}{4(s_L+2s_\Delta)} + \frac{2s_L^2+5s_Ls_\Delta+s_\Delta^2}{2(s_L+2s_\Delta)}\lambda_{K_E} - \frac{4s_L^2+7s_Ls_\Delta-s_\Delta^2}{4(s_L+2s_\Delta)}\lambda_{K_E}^2 - K_I$
$\Gamma^E$	$\frac{3}{2}s_L$	$\frac{(7\sqrt{2}-8)s_L+(8\sqrt{2}-8)s_\Delta}{8s_L+8s_\Delta}$	$x_1$	$\frac{(448\sqrt{2}-597)(2647s_L+2472s_\Delta-220s_\Delta\sqrt{2})(17s_L+4s_\Delta\sqrt{2}+24s_\Delta)s_L}{5759872(s_L+s_\Delta)^2}$

Table 4: Equilibrium Outcome for  $\Gamma$