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Signaling Quality in the Presence of Observational Learning

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Abstract
We study the optimal pricing strategy for a privately informed monopolist in the presence of observational learning. Early adopters learn quality before purchasing the product. Late adopters learn quality from first-period price and early adopters' purchase decisions. Prices generate revenues, signal quality, and determine information transmission through observational learning. Separation may occur through either high or low prices, depending on the elasticity of early adopters' demand. When demand for good-quality products is less elastic, high prices are less costly for high-type firms due to static and dynamic effects. High-type firms are marginally less affected by high prices, since they lose fewer consumers. Moreover, early sales at higher prices carry good news about quality to late adopters. The opposite occurs when the demand for good-quality products is more elastic.

Keywords Early adopters · Monopoly · Observational learning · Pricing strategy · Signaling

1 Introduction

Markets for innovative products are characterized by uncertainty about product quality.[1] Consider, for example, high-tech consumer electronics (e.g., smart-phones and computers), and digital products (e.g. apps and computer software). Although sellers are often better informed about product features, only consumers can rate the match between these features and their specific needs. It is possible that a perfectly

[1] We interpret quality as the match between product features and consumers' tastes.

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engineered product—which is thought to satisfy consumer's desires as expressed in marketing surveys—may leave consumers cold in the end.[2] Other products, such as personal computers in the 1980s or the iPod in the early 2000s, can take the market by storm: fulfilling needs that not even consumers knew they had.

In these markets, consumers may learn by observing others' choices: observational learning. In particular, late adopters tend to infer high quality from the number of early adoptions of a new product.[3] Since adoption is costly for new technological products, which are expensive, observational learning is a credible and trustworthy source of information.[4] Indeed, a product's success often depends on how well it performs with the—usually small—group of early adopters. Therefore, the optimal pricing strategy must take into account both the presence of asymmetric information and observational learning. Prices, besides generating revenue, signal the firm's confidence in the technical features of the product, but also determine the amount of information that is transmitted through early adopters' purchase decisions.

We consider a two-period model in which a long-lived monopolist sells a new product of uncertain quality to a sequence of short-lived consumers. The monopolist is privately informed about the probability of producing good-quality products. Early adopters learn about quality by observing a private quality signal and the posted price. Late adopters, on the other hand, learn about product quality by observing public history: past price and early adopters' purchase decision. Therefore, we assume that consumers are able to recognize not only expensive or cheap products, but also a trending or fading new release. This is reasonable in markets for innovative and technological products, where new releases are frequent and consumers can compare a new product's price and sales to a well-established benchmark.

We analyze conditions for the existence of separating equilibria in which high or low prices act as signals of quality. Our main result is that separation might occur through high or low prices (with respect to the full-information monopoly price) depending on the elasticity of demand for good-quality products. Skimming pricing—which involves signaling through high prices—is used when good-quality products face a less elastic demand. On the one hand, a high-type firm loses fewer consumers in the introductory period. Moreover, sales at high prices are more informative about quality for late adopters. Penetration pricing, on the other hand, is used when good quality is associated with greater elasticity. Here, low prices signal the firm's willingness to forgo margin for quantity, and can be also interpreted as a

[2] Philips attempted to enter the video-game market in the late 80s with the release of the "Compact Disk Interactive" (CD-i), a console that contained educational games and also played normal CDs. A high introductory price ultimately doomed the CD-i, as consumers opted for Nintendo gaming systems that sold for half the price of a new CD-i.

[3] Restaurants with a considerable waiting list, bestselling books, and high-click-volume online offerings are usually perceived as high-quality products. Similarly, a residential property that spends too much time on the market can start a bad news snowball.

[4] Information transmission might also occur through word-of-mouth communication (WOM) among consumer generations. We consider that observational learning fits better the class of products we have in mind. Since adopters are putting money behind their decisions, there is no concern about "fake reviews"; and information that is transmitted through observational learning is more credible and trustworthy than is WOM.

gamble about massive adoption at low prices, which will generate better news for future consumers.

Our analysis sheds new light on skimming versus penetration pricing strategies.[5] For example, Apple embraced a skimming strategy for its flagship products, such as the iPhone: Apple introduced them at a high price and expected early adopters—in spite of high prices—to convey the good news about quality to late adopters. However, Apple recently switched to a penetration strategy for its EarPods: Apple charged low prices and expected massive levels of sales to convey the good news.[6] Our model can help explain this move as a switch from a market where good quality implies a more inelastic demand, due to loyal consumers, to another where good quality means a broader consumer base, due to new adoption.

2 Related Literature

This paper is related to the literature on observational learning, in which consumers learn quality by observing other agents' actions (for example past purchase decisions). Seminal papers by Banerjee (1992) and Bikhchandani et al. (1992) illustrate how it may lead to herding behavior, where new consumers disregard their own private information and imitate past consumers' actions. Through pricing decisions, firms might manipulate consumer learning to maximize profits.

When both firms and consumers are uncertain about quality, low introductory prices are optimal since they accelerate experimentation and information transmission through higher sales (Bergemann and Valimaki 1996; Caminal and Vives 1996; Schlee 2001). When consumers receive a private signal about product quality, high initial prices allow the seller to screen consumer's private information and facilitate information transmission to future buyers (Bose et al. 2006, 2008). Bergemann and Valimaki (2006) show that when the full-information monopoly price exceeds the valuation of new consumers (niche market), a penetration pricing strategy is optimal to capture a large market share. The opposite happens in mass markets, where the monopoly price is lower.

In general, a sequential selling scheme that allows the firm to spread out information by letting subsequent consumers observe past purchase history is preferred to a simultaneous selling strategy (Sgroi 2002; Liu and Schiraldi 2012; Bhalla 2013; Aoyagi 2010). The choice of having a product tested before launching it might also be used as an instrument to influence learning by subsequent consumers (Taylor 1999; Gill and Sgroi 2012).

This paper is also closely related to the literature on signaling quality through prices. When marginal costs and quality are correlated, lower sales due to high

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[5] Market skimming refers to introducing the product at a high price for early adopters, then gradually lowering the price to attract thriftier consumers. Penetration pricing refers instead to an initial low price for a new product that increases after information spreads out (Kotler and Armstrong 2010).

[6] https://www.nytimes.com/2011/10/24/technology/apples-lower-prices-are-all-part-of-the-plan.html http://fortune.com/2017/03/17/apple-pricing-strategy/.

prices are less damaging to the high-quality producer (Bagwell and Riordan 1991). Similarly, when consumers receive a private signal about quality, a high-quality seller will signal through high prices, confident that consumers already have some corroborating information (Judd and Riordan 1994). Finally, when word-of-mouth communication (WOM) among subsequent consumer generations is allowed, low prices signal high quality. Since low prices encourage experimentation—which in turn amplifies the (good) news about product quality that is transmitted to future consumers—high-quality firms are more willing to use them to signal quality (Guadalupi 2018).We contribute to both strands by allowing for private information on the firm side and for consumers to learn from both past purchases and prices.

A few papers study signaling in the presence of observational learning. Taylor (1999) considers a house that is for sale over two periods. Since a purchase ends the game, positive observational learning can never occur, so that prices are used to prevent negative herding. He shows that a failure to sell at low prices can do irreparable damage to a product image, while high prices induce future consumers to think that the house did not sell because it was expensive, and not because of poor quality. We generalize this model by allowing both positive and negative observational learning. Moreover we focus on separating equilibria (impossible in Taylor's model since low-quality houses are worthless), and therefore on the dual role of prices: signaling and information transmission.

The paper that is closest to ours is Miklós-Thal and Zhang (2013), who show that firms have incentives to reduce marketing effort (demarketing) to signal product quality. In their model, late consumers can attribute a lack of sales to either poor quality or inattention due to the lack of marketing effort. Demarketing then helps to shift attention away from poor quality after the absence of a sale. In our model a high introductory price plays a similar role as demarketing in Miklós-Thal and Zhang (2013). We complement their analysis by focusing on separating equilibria and showing that a low introductory price—which translates into high marketing effort—might also be used to signal quality.

Signaling may also occur through the decision to sell or not (Bar-Isaac 2003) or the decision to display past sales as in the case of a daily deal website (Subramanian and Rao 2016). Finally, early adopters play a crucial role in Subramanian and Rao (2016) and Despotakis et al. (2017) for the existence of a separating equilibrium, where signaling occurs through the selling mechanism (posted prices vs. auctions).

The paper proceeds as follows: In Sect. 3 we introduce the model. In Sect. 4 we present the main results. In Sect. 5 we illustrate our results through two examples. Section 6 concludes.

3 The Model

We consider a two-period model in which a long-lived monopolist sells a product of uncertain quality. Quality can be either good or bad: $q \in \{0, 1\}$. The monopolist is privately informed about his type $\theta \in \{H, L\}$, the probability of producing good-quality products, $\theta = \mathbb{P}(q = 1)$, with $0 < L < H < 1$.[7] Quality is exogenous and is unrelated to marginal costs, which we assume to be zero for both types. This is realistic when quality-related investments are sunk (see e.g. Stock and Balachander 2005).[8] The monopolist chooses prices, and there is no discounting.

The seller faces a sequence of short-lived consumers. There is a continuum of early adopters of mass $\lambda \in (0, 1)$ at $t = 1$, and a continuum of late adopters of mass 1 at $t = 2$. We assume $\lambda << 1$ to focus on information transmission by early-adopters' purchase decisions (observational learning), rather than their direct effect on profits. Consumers have unit demand for the product and receive satisfaction $f_t(q, v_t)$ from purchasing and zero otherwise. Satisfaction $f_t(q, v_t)$ is increasing in quality q and in v_t: an idiosyncratic shock that is independently drawn from distribution $G(v_t)$.[9]

Early adopters, while a small fraction of the market, are knowledgeable about the industry. They receive a private quality signal, $s = q + \varepsilon$, where ε represents white noise, and we denote by $h(s \mid q)$ the conditional distribution of the private signal given quality. Late adopters learn product quality from public history: the first-period price and purchase decisions. The timing of the game is as follow: the monopolist perfectly learns θ and chooses the introductory price P. Given P and s, early adopters update their beliefs about quality and make a purchase decision. After observing early adopters' purchase decisions and P, late adopters update their beliefs about q. The firm chooses the second-period price (P_2) and consumers decide whether to buy or not.[10]

Consumers share the prior belief μ_0 that product quality is good. After observing P, they form the interim belief $\mu := \mathbb{P}(q = 1|P)$. After receiving the private signal, early adopters update beliefs to $\mu_1(\mu, s) = \mathbb{P}(\mathrm{q} = 1 \mid \mu, \mathrm{s})$, and buy if and only if $E_{\mu_1(\mu,s)}\left[f_1(q, v_1) - P\right] \geq 0$.

First-period demand is given by $\widetilde{D}(P, \mu, s)$, the expected value of which is $\overline{D}(P, \mu, q)$; this is increasing in quality and in beliefs, and is decreasing in prices.[11] First-period expected demand is then given by:

$$D(\theta, P, \mu) = \theta\overline{D}(P, \mu, 1) + (1 - \theta)\overline{D}(P, \mu, 0). \tag{1}$$

Late adopters know the market structure: prices and market size. In practice, they are able to distinguish high versus low prices (with respect to the full-information monopoly price) so that prices act as effective signals. Moreover, they understand when the demand for good-quality (bad-quality) products is high or

[7] We consider persistent types. A monopolist of type θ produces a good-quality product with probability θ in each period. Moreover quality is the same for all units produced in each period. Therefore, the monopolist perfectly learns quality after first-period production.

[8] Moreover, this assumption fits well the notion of quality as the match between product features and consumers' tastes.

[9] Note that consumers might also be interested in buying bad-quality products.

[10] It is inconsequential if the firm learns product quality at the end of the first period. Only consumers' beliefs are relevant for the pricing decision. In fact, second-period prices maximize profits given beliefs with no rationale for signaling.

[11] Specifically, $\overline{D}(P, \mu, q) = \int_s \widetilde{D}(P, \mu, s)h(s \mid q)ds$. With the standard assumption that f is increasing in both q and v, it is easy to show that the demand $\tilde{D}(P, \mu, s)$ and its expectation $\bar{D}(P, \mu, q)$ are increasing in q (s), and in μ and are decreasing in P.

low to make sense of sales. Given early adopters decision to purchase ($d = Y$) or not ($d = N$), they update beliefs to $\mu^d(P,\mu)$,with $d \in \{Y, N\}$:

$$\mu^Y(P,\mu) = \frac{1}{1 + \frac{(1-\mu)}{\mu}\frac{\overline{D}(P,\mu,0)}{\overline{D}(P,\mu,1)}}$$
$$\mu^N(P,\mu) = \frac{1}{1 + \frac{(1-\mu)}{\mu}\frac{\left[1-\overline{D}(P,\mu,0)\right]}{\left[1-\overline{D}(P,\mu,1)\right]}}$$

and they buy if and only if $E_{\mu^d(P,\mu)}\left[f_2\left(q, v_2\right) - P_2\right] \geq 0$, which leads to aggregate second-period demand $D\left(P_2, \mu^d(P,\mu)\right)$, with associated profits $\pi\left(\mu^d(P,\mu)\right)$. As types are persistent, signaling occurs only in the first period. Thus, second-period prices maximize $\pi\left(P_2, \mu^d(P,\mu)\right) = P_2 D\left(P_2, \mu^d(P,\mu)\right)$, which leads to optimal profits $\pi\left(\mu^d(P,\mu)\right)$, which are increasing and convex in beliefs.

Note that $\mu^Y(P,\mu)$ and $\mu^N(P,\mu)$ are both increasing in μ: the beliefs that are generated through signaling. However, they are not necessarily increasing in P. In particular, μ^Y is increasing in P if and only if $\frac{\overline{D}(P,\mu,1)}{\overline{D}(P,\mu,0)}$ increases in P. Following Milgrom (1981), we denote $\frac{\overline{D}(P,\mu,1)}{\overline{D}(P,\mu,0)}$ as the "good news" that is carried by a sale. Similarly, μ^N increases in P if and only if the good news from a no-sale event—$\frac{\left[1-\overline{D}(P,\mu,1)\right]}{\left[1-\overline{D}(P,\mu,0)\right]}$—is increasing in P. This shows that the quality update after observational learning depends on the *relative likelihood* (between good and bad quality) of sales at a given price.

Let $\Pi(\theta, P, \mu)$ denote the expected profits of a monopolist of type θ who charges the price P in the first period, which induces beliefs μ after signaling:

$$\begin{aligned}\Pi(\theta, P, \mu) = &\lambda P D(\theta, P, \mu) + D(\theta, P, \mu)\pi\left(\mu^Y(P,\mu)\right) \\ &+ (1 - D(\theta, P, \mu))\pi\left(\mu^N(P,\mu)\right).\end{aligned} \tag{2}$$

In particular, first-period profits are proportional to the mass of early adopters in the market. Second-period profits are calculated in the following way: With probability $D(\theta, P, \mu)$ a sale occurred so that beliefs are updated to $\mu^Y(P,\mu)$, with corresponding second-period profits $\pi\left(\mu^Y(P,\mu)\right)$. Similarly, with probability $1 - D(\theta, P, \mu)$ beliefs are updated after a no-sale to $\mu^N(P,\mu)$, and second-period corresponding profits are $\pi\left(\mu^N(P,\mu)\right)$.

We define and analyze conditions for the existence of separating equilibria in pure strategies and show that signaling can occur through both high and low prices. We finally provide an example for each case.

4 Separating Equilibria

A separating equilibrium is a perfect Bayesian equilibrium such that consumers can infer the firm's type and therefore expected product quality by observing the introductory price. A separating equilibrium is a pair of prices $\left(P^L, P^H\right)$ that induce beliefs $\mu = L$ if $P = P^L$, and $\mu = H$ if $P = P^H$. Moreover, off-equilibrium prices $P \neq \left\{P^L, P^H\right\}$ are assumed to induce beliefs $\mu = L$, since any deviation is interpreted as coming from a low type.

Definition 1 *A (first-period) separating equilibrium is a pair* $\left(P^L, P^H\right)$ *such that*:

C1. $\Pi\left(L, P^L, \mu = L\right) \geq \Pi(L, P, \mu = L)$, for every $P \neq P^H$;
C2. $\Pi\left(L, P^L, \mu = L\right) \geq \Pi\left(L, P^H, \mu = H\right)$; and
C3. $\Pi\left(H, P^H, \mu = H\right) \geq \Pi(H, P, \mu = L)$, for every $P \neq P^H$.

For the low-type monopolist, the equilibrium price P^L must dominate any price $P \neq P^H$ that induces the same beliefs $\mu = L$ (C1). Moreover, the low type should not have incentives to mimic the high type, even if this implies beliefs $\mu = H$ (C2). Finally, for the high type, P^H must dominate any other price P, with the knowledge that any deviation will be treated as coming from a low-type seller (C3).

Therefore, the low type cannot do better than to behave as in the complete-information setting, and chooses the full-information monopoly price. If the high type is to separate, then he must choose a price that the low type would not find profitable to mimic, and from which he would not deviate.

Lemma 2 *A separating equilibrium is a pair* $\left(P^L, P^H\right)$ *such that* $P^L = P^{L^*}$, *which is the low type full-information monopoly price, and* P^H *satisfies:*

1. $\Pi\left(L, P^{L^*}, \mu = L\right) \geq \Pi\left(L, P^H, \mu = H\right)$
2. $\Pi\left(H, P^H, \mu = H\right) \geq \Pi\left(H, P^{H^*}, \mu = L\right)$

where P^{H^*} maximizes high-type monopolist's expected profits under beliefs $\mu = L$, $\Pi(H, P, \mu = L)$.

Proof See "Appendix". □

4.1 Existence and Characterization of Separating Equilibria

We now show that separating equilibria exist, in which the high-type firm might choose either high or low prices to signal quality. To focus on the case in which signaling is costly, we assume that the high-type monopoly price $P^{H^{**}}$[12] would be mimicked by a low type, or equivalently $\Pi\big(L, P^{H^{**}}, \mu = H\big) > \Pi\big(L, P^{L^{*}}, \mu = L\big)$.

Definition 3 *Separation occurs through high* (*low*) *prices if the separating equilibrium price that is chosen by the high type is higher* (*lower*) *than the monopoly price*, $P^H > (<) P^{H^{**}}$.

The possibility of separation is related to the existence of an action that is marginally less costly for high types: the standard single-crossing property from the signaling literature (SCP1). In our setting, a second single-crossing property (SCP2) is needed, which requires that an increase in consumers' beliefs is more valuable to the high type.[13] More specifically, SCP1 implies that higher (lower) prices are marginally less costly for the high-type monopolist. This is equivalent to the cross-derivative with respect to price and type to be signed:

$$\begin{aligned}\frac{\partial^2\Pi(\theta,P,\mu)}{\partial\theta\partial P} =& D_{\theta P}(\theta,P,\mu)\big[\lambda P + \pi\big(\mu^Y(P,\mu)\big) - \pi\big(\mu^N(P,\mu)\big)\big] \\ &+ D_\theta(\theta,P,\mu)\left[\lambda + \left(\frac{\partial\pi\big(\mu^Y(P,\mu)\big)}{\partial\mu^Y(P,\mu)}\frac{\partial\mu^Y(P,\mu)}{\partial P}\right.\right. \\ &\left.\left. - \frac{\partial\pi\big(\mu^N(P,\mu)\big)}{\partial\mu^N(P,\mu)}\frac{\partial\mu^N(P,\mu)}{\partial P}\right)\right] \gtrless 0.\end{aligned} \tag{3}$$

Note that prices have both a static and dynamic effect on profits, and these effects are interrelated: The static effect is driven by the price-sensitivity of (first-period) demand. In particular, if $D_{\theta P}(\theta,P,\mu) = \overline{D}_P(P,\mu,1) - \overline{D}_P(P,\mu,0) \geq 0$, then the demand for good-quality products is less price-sensitive than is the demand for bad-quality ones. Thus a price increase is less costly for high-type firms, which are more likely to produce good-quality products.

The dynamic effect is driven by the price-sensitivity of second-period beliefs, which jump to $\mu^Y(P,\mu)$ when a sale in $t=1$ occurred, and to $\mu^N(P,\mu)$ otherwise. The difference $\mu^Y(P,\mu) - \mu^N(P,\mu)$ reflects the amount of information that is conveyed by early adopters' purchase decision. If $\frac{\partial}{\partial P}\left[\mu^Y(P,\mu) - \mu^N(P,\mu)\right] \geq 0$, then information transmission is higher at high prices.[14] In other words, the "good news" that is generated by first-period sales is a complement with prices. Since a high-type

[12] The high-type full-information monopoly price $P^{H^{**}}$ is the maximizer of $\Pi(H,P,\mu=H)$.

[13] In Spence's job-market signaling model, high-type workers signal their type via increased education, which low types are unable to replicate because education is more costly for them (SCP1). SCP2 is automatically satisfied due to the quasilinear structure of the worker's utility function: $w(\mu) - c(e,\theta)$, where an increase in beliefs is equally valuable for all types.

[14] Convexity of π implies that the effect on second-period profits of information transmission is higher when first-period prices are high.

monopolist is more likely to sell, then a high price is informationally more advantageous for it.

If both the static and dynamic effects are positive, then SCP1 holds with a positive sign, and we can expect separation through high prices.

The same can happen with an opposite sign. If the demand for good-quality products is more price-sensitive $(D_{\theta P}(\theta, P, \mu) = \overline{D}_P(P, \mu, 1) - \overline{D}_P(P, \mu, 0) \leq 0)$, then high prices are more detrimental to high-type firms due to a static effect on profits. Moreover, if beliefs are more sensitive to early adopters' purchase decision at lower prices $(\frac{\partial}{\partial P}[\mu^Y(P, \mu) - \mu^N(P, \mu)] \leq 0)$, high prices are more costly to high-type firms.

If both the static and dynamic effects are negative, then SCP1 holds with a positive sign, and we can expect separation through low prices.[15]

Consider now SCP2, which requires an increase in consumers' beliefs to be more valuable to the high type, which is equivalent to:

$$\begin{aligned}\frac{\partial^2 \Pi(\theta, P, \mu)}{\partial \theta \partial \mu} =& D_{\theta\mu}(\theta, P, \mu)\left[\lambda P + \pi\left(\mu^Y(P, \mu)\right) - \pi\left(\mu^N(P, \mu)\right)\right] \\ &+ D_\theta(\theta, P, \mu)\left(\frac{\partial \pi\left(\mu^Y(P, \mu)\right)}{\partial \mu^Y(P, \mu)} \frac{\partial \mu^Y(P, \mu)}{\partial \mu} \right. \\ &\left. - \frac{\partial \pi\left(\mu^N(P, \mu)\right)}{\partial \mu^N(P, \mu)} \frac{\partial \mu^N(P, \mu)}{\partial \mu}\right) \geq 0.\end{aligned}$$

If $D_{\theta\mu}(\theta, P, \mu) = \overline{D}_\mu(P, \mu, 1) - \overline{D}_\mu(P, \mu, 0) > 0$, higher beliefs, which are generated through signaling, benefit more the demand for good-quality products. This is marginally more convenient for the high type, which produces good quality more often. Moreover, if $\frac{\partial}{\partial \mu}[\mu^Y(P, \mu) - \mu^N(P, \mu)] \geq 0$, information transmission is higher at higher (signaling) beliefs. In other words, higher beliefs, which are generated through signaling, induce a bigger difference in second-period beliefs between a history of sale and one of no-sale, which in turn guarantees more information transmission about quality.

Propositions 4 and 5 formalize this intuition for the case in which separation occurs through high and low prices, respectively:

Proposition 4 *Sufficient conditions for the existence of a separating equilibrium* $\left(P^{L^*}, P^H\right)$ *wherein* $P^H > P^{H^{**}}$ *are given by:*

[15] In this case, it is also needed that the incentive of a high-type monopolist to extract rent from inframarginal consumers in the first period is small, which is easily satisfied for $\lambda << 1$. The specific condition that λ must satisfy is given in condition 2 of Proposition 5.

1. $D_{\theta P} > 0$
2. $\frac{\partial \mu^Y(P,\mu)}{\partial P} - \frac{\partial \mu^N(P,\mu)}{\partial P} \geq 0$
3. $D_{\theta_\mu} \geq 0$, and $\frac{\partial \mu^Y(P,\mu)}{\partial \mu} - \frac{\partial \mu^N(P,\mu)}{\partial \mu} \geq 0$.

Proposition 5 *Sufficient conditions for the existence of a separating equilibrium* $\left(P^{L^*}, P^H\right)$ *wherein* $P^H < P^{H^{**}}$ *are given by:*

1. $D_{\theta P}(\theta, P) < 0$
2. $\frac{\partial \mu^Y(P,\mu)}{\partial P} - \frac{\partial \mu^N(P,\mu)}{\partial P} \leq -\lambda$
3. $D_{\theta_\mu} \geq 0$, and $\frac{\partial \mu^Y(P,\mu)}{\partial \mu} - \frac{\partial \mu^N(P,\mu)}{\partial \mu} \geq 0$.

Both the static and dynamic signaling mechanisms operate through the relative price-sensitivity of demand between good and bad-quality products. If the demand for good-quality products is less price-sensitive, both the static and dynamic effect of prices on profits lead to high prices as a signaling tool. On the one hand, the high-type monopolist suffers less from charging high prices since it loses fewer consumers than does a bad-quality producer. More interestingly, early adopters' purchase decisions are more informative at high prices. In fact, at high prices good-quality products sell more often than do bad-quality ones, which in turn leads to better news about quality when, in spite of such high prices, there is a sale.

The opposite happens when price sensitivity is greater for good-quality products. Now it is sales at low prices that generate better inference about quality. See the "Appendix" for a more detailed discussion of the technical conditions (Corollary 10).

A different rationale for signaling appears in models where quality and marginal costs are correlated (Bagwell and Riordan 1991). High prices generate lower sales, which cause less damage to a higher-cost (higher-quality) producer. Our mechanism, on the other hand, emphasizes the role of demand on signaling through observational learning. Introducing correlation between quality and costs would give an extra incentive to the high-type seller to charge a high price. Nevertheless it could weaken our result of signaling through low prices for a sufficiently large cost difference.

5 Examples

We now present two examples to illustrate our results. To make our point we consider the simpler version of the model in which early adopters are perfectly informed about product quality. In this case, they do not rely on price information (signaling) when deciding whether to buy or not. Nevertheless, signaling remains relevant for late adopters, who learn from both first-period prices and purchase decisions. In this case first-period demand is given by $\overline{D}(P, q)$, which is increasing in quality q and is decreasing in price. First-period expected demand is then given by:

$$D(\theta, P) = \theta\overline{D}(P, 1) + (1-\theta)\overline{D}(P, 0).$$

5.1 High Prices Signal Quality: Disruptive Innovation

Consider a firm that introduces a potentially drastic innovation that, if successful, would disrupt the market. This was the case of the first iPhone or iPod that was introduced by Apple. Such a situation leads to a more inelastic demand for good-quality products, which makes high prices less costly for the high-type monopolist. This, in turn, induces a separating equilibrium involving skimming, with high introductory prices.

To be specific, consider the case where a good-quality innovation becomes a "must have" product: a proportion $(1-\gamma)$ of consumers become completely price insensitive (up to v):

$$\bar{D}(P, 1) = (1-\gamma)1_{(P \leq v)} + \gamma\bar{D}(P, 0), \gamma < 1$$

In this case $D_{\theta P} > 0$, since a high-type firm, which is more likely to produce good quality, will face consumers less sensitive to prices. Moreover, with this demand structure, not selling in the first period generates the same beliefs irrespective of prices: $\frac{\partial\mu^N}{\partial P} = 0$. A sale, however, generates better beliefs at higher prices: $\frac{\partial\mu^Y}{\partial P} \geq 0$. Then $\frac{\partial\mu^Y}{\partial P} - \frac{\partial\mu^N}{\partial P} \geq 0$, so that information transmission is greater at high prices. Intuitively, the marginal gain of a first-period sale is greater when the price is higher. Since a high-type firm, which is more likely to produce good quality, sells more often, it benefits more from sales at high prices, for both the static and dynamic effect.

Finally as early-adopters purchase decisions are independent of signaling, a sufficient condition for SCP2 to be satisfied is $\frac{\partial\mu^Y}{\partial\mu} - \frac{\partial\mu^N}{\partial\mu} \geq 0$, which is implied by the condition in Corollary 6. Corollary 6 is true whenever μ is sufficiently small. Otherwise, an increase in μ makes agents too confident about good quality, which in turn makes a first-period sale irrelevant. Corollary 6 provides an upper bound on the highest possible belief H that is generated through signaling.

Corollary 6 *If* $\left(\frac{H}{1-H}\right)^2 \leq \frac{\bar{D}(v,0)}{\gamma\left[1-\gamma\left(1-\bar{D}(v,0)\right)\right]}$, *then separation occurs through high prices.*

Therefore a market such that good-quality products face more inelastic consumers, is characterized by separation through high prices. A high-type monopolist is more willing to increase prices to extract rent, since it loses fewer consumers. Moreover, sales at high prices amplify good news about product quality, which in turn reinforce the static revenue effect. A skimming pricing strategy can therefore characterize the introduction of disruptive innovations.

5.2 Low Prices Signal Quality: Incremental Innovation

We now consider a firm that introduces a new version of an existing product: for example, Earpods by Apple. If quality is bad, only consumers who already identify with the brand will buy it: switching from an older version to the new one. However, good-quality products will also appeal to those who have been purchasing from a different firm in the past. This implies that good-quality products will face a more elastic demand (due to a scale effect), which makes low prices less costly for the high-type firm, and penetration pricing the optimal signaling strategy.

To be specific, consider the demand function:

Assumption $\bar{D}(P,1) = \alpha\bar{D}(P,0)$, where $\alpha > 1$ represents the relative size of the market that is available to a good-quality product versus a bad-quality one.

It is easy to see that in this case $D_{\theta P} < 0$. High-type firms, which have access to a larger market, lose more consumers when prices increase. Moreover, with this demand structure, a sale in the first period generates the same beliefs irrespective of prices ($\frac{\partial \mu^Y}{\partial P} = 0$). Not selling, however, is better (in terms of the inference on quality) when prices are high, $\frac{\partial \mu^N}{\partial P} \geq 0$. Then, $\frac{\partial \mu^Y}{\partial P} - \frac{\partial \mu^N}{\partial P} \leq 0$, so that information transmission is higher at low prices. Intuitively, the marginal gain from a first-period sale is greater the lower is the price. A high-type seller, which is more likely to produce good quality, sells more often, and therefore benefits more from a low price. Since the low type sells less often, it prefers to hide behind a high price.

We need to show only that the information transmission role of early-adopters' purchase decisions is relevant as compared to revenue-generating concerns: $\frac{\partial \mu^N}{\partial P} \geq \lambda$, which is implied by the first condition in Corollary 7. If revenue generation concerns are small (λ sufficiently small), this is always satisfied, since any increase in the amount of information that is transmitted (through no sales, for example) is more important.

Moreover, since signaling does not affect early-adopters purchase decisions, a sufficient condition for SCP2 to be satisfied is $\frac{\partial \mu^Y}{\partial \mu} - \frac{\partial \mu^N}{\partial \mu} \geq 0$, which is true whenever μ is sufficiently small. Otherwise, an increase in μ makes agents too confident about good quality, then a first-period sale is irrelevant. The second condition in Corollary 7 provides an upper bound on the highest possible belief H that is generated through signaling.

Corollary 7 *If*

- $\mu^{N2}\frac{1-H}{H}(\alpha-1)|\bar{D}_P(P,0)| \geq \lambda$
- $\left[\frac{H}{1-H}\right]^2 \leq \alpha$, then low prices signal high quality.

Therefore, a market such that the demand for good-quality products is a scaled-up version of the demand for bad-quality products, is characterized by separation through low prices. In particular, low prices are more costly for a low-type monopolist, both because of a lower (average) price sensitivity, and the fact that a no-sale (more likely at high prices and for the low type) is the only event that carries information about quality. A penetration pricing strategy can therefore characterize the introduction of incremental innovations.

6 Conclusion

This paper studies the optimal introductory price for a new product in a dynamic monopoly model with private information about quality and observational learning. Quality is interpreted as the match between product's features and consumers' tastes. The firm is privately informed about its type: the probability of producing good-quality products (products consumers are more likely to like, given their specific characteristics). Early adopters receive a private signal about quality before deciding whether to make a purchase. Late adopters learn quality by observing past prices and early adopters' purchase decisions.

Prices here play three roles: they generate revenues; they act as signals of the firm's type; but they also facilitate (or impede) information transmission between consumers' generations.

Our main result is that signaling can occur through both high and low prices, depending on the elasticity of early adopters' demand. In particular, demand elasticity operates through both a static and dynamic mechanism. If demand for good-quality products is less elastic (relatively to bad-quality products) then high-type firms, which are more likely to produce good-quality, are marginally less affected by high prices. Similarly, since a higher price induces a bigger difference in beliefs between a history of sale and one of no-sale, and a high-type monopolist is more likely to sell, a high price is informationally more advantageous for the high-type monopolist. The opposite reasoning is true for the case in which good-quality products are characterized by a more elastic demand.

Our work sheds new light on skimming versus penetration pricing strategies, as well as helping explain business strategies such as Apple's switching from high to low prices. We also provide two examples of markets (and products) where our prediction could be applied, and show that in the case of disruptive (incremental) innovations high (low) prices can be used as signals of quality.

Several extensions may follow from this two-period framework: First, it would be interesting to consider the case in which firms could offer a special deal to early adopters in order to manipulate their purchase decisions, and thus influence information transmission to second-period consumers. Moreover, learning from early adopters' purchase decisions and also from reviews and/or from word-of-mouth (WOM) could give new insights on the optimal pricing strategy. Finally, competition among two or more firms could lead to interesting price dynamics as well as the possible interaction between separating and pooling equilibria.

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Appendix A

Lemma 8 *There exists a separating equilibrium* $\left(P^{L^*}, P^H\right)$ *in which separation occurs through high (low) prices if*

(SCP1) $\frac{\partial^2 \Pi(\theta,P,\mu)}{\partial\theta\partial P} > (<)0$

(SCP2) $\frac{\partial^2 \Pi(\theta,P,\mu)}{\partial\theta\partial \mu} > 0.$

Proof We consider two candidates for separating equilibrium: The first one involves separation through high prices, and the second one separation through low prices. In both cases we define a price $P^H = \overline{P}$ (higher and lower than $P^{H^{**}}$, respectively) such that the low-type monopolist is indifferent between following the equilibrium strategy and mimicking the high-type one:

$$\Pi\left(L, \overline{P}, \mu = H\right) - \Pi\left(L, P^{L^*}, \mu = L\right) = 0.$$

A separating equilibrium in which high prices signal high quality exists if at the price $\overline{P}$ the high-type monopolist has no incentive to deviate:

$$\Pi\left(H, \overline{P}, \mu = H\right) - \Pi\left(H, P^{H^*}, \mu = L\right) \geq 0 = \Pi\left(L, \overline{P}, \mu = H\right) - \Pi\left(L, P^{L^*}, \mu = L\right). \tag{4}$$

For 4 to be satisfied, the following two conditions are sufficient:

$$\Pi\left(H, \overline{P}, \mu = L\right) - \Pi\left(H, P^{H^*}, \mu = L\right) \geq \Pi\left(L, \overline{P}, \mu = L\right) - \Pi\left(L, P^{L^*}, \mu = L\right) \tag{5}$$

$$\Pi\left(H, \overline{P}, \mu = H\right) - \Pi\left(H, \overline{P}, \mu = L\right) \geq \Pi\left(L, \overline{P}, \mu = H\right) - \Pi\left(L, \overline{P}, \mu = L\right), \tag{6}$$

which are directly implied by SCP1 and SCP2.

SCP1 and SCP2 are sufficient conditions for the existence of separation through high prices. Note first that SCP1 implies directly that $P^{H^*} > P^{L^*}$. When allowed to choose the optimal price, the high-type monopolist will prefer to set a higher price than the low-type one, holding beliefs constant. This is so because higher prices are marginally less costly for the high-type monopolist. Since beliefs affect profits in a non-separable way, an additional assumption is needed to guarantee separation. SCP2 implies that the shift from pessimistic to optimistic beliefs is more attractive to the high-type firm. Finally, note that these are sufficient conditions, and separation could still exist under less restrictive assumptions, even though it makes the economic analysis and interpretation more complex. The same reasoning applies for the case in which low prices signal high quality. □

Lemma 9 *The only equilibrium that satisfies the intuitive criterion is* $\left(P^{L*}, \overline{P}\right)$, *where the price charged by the high-quality monopolist is the least costly among the ones that induce separation:* $P^H = \bar{P}$ *such that*

$$\Pi\left(L, \overline{P}, \mu = H\right) = \Pi\left(L, P^{L^*}, \mu = L\right).$$

Proof A separating equilibrium $\left(P^{L*}, P^H\right)$ satisfies the intuitive criterion if there is no price $P^{'}$ such that: a) $\Pi\left(H, P^{'}, \mu = H\right) \geq \Pi\left(H, P^H, \mu = H\right)$; and b) $\Pi\left(L, P^{'}, \mu = H\right) < \Pi\left(L, P^{L*}, \mu = L\right)$. If there exists a price $P^{'}$ such that the high type prefers to deviate and the low type prefers to stick to the equilibrium strategy, consumers should interpret such a deviation as if coming from a high type, which would collapse the equilibrium in the first place. Then the only equilibrium that satisfies the intuitive criterion is the least-costly for the high type: the one in which the high-type monopolist charges the lowest (highest) of the prices that the low-type one would not find profitable to mimic. We now show that $\left(P^{L^*}, \overline{P}\right)$ is the only equilibrium that satisfies the intuitive criterion. We prove the result for the case in which separation occurs through high prices. We first show that there is no equilibrium price $P > \overline{P}$ that satisfies the intuitive criterion. Consider the price $P > \overline{P}$ such that $\left(P^{L^*}, P\right)$ is a separating equilibrium. Define $P^{'} = P - \epsilon$. Then it is easy to see that: a) $\Pi\left(H, P^{'}, \mu = H\right) \geq \Pi(H, P, \mu = H)$; and b) $\Pi\left(L, P^{'}, \mu = H\right) < \Pi\left(L, P^{L^*}, \mu = L\right)$. Noting that $P^{H^{**}} < \overline{P}$ (signaling is costly), it follows that $P^{H^{**}} < P^{'} < P$. Therefore $\Pi\left(H, P^{'}, \mu = H\right) \geq \Pi(H, P, \mu = H)$. Moreover we know by Lemma 4 that $\Pi(L, P, \mu = H) < \Pi\left(L, P^{L^*}, \mu = L\right)$. Then by continuity $\Pi\left(L, P^{'}, \mu = H\right) < \Pi\left(L, P^{L^*}, \mu = L\right)$. Thus for any price $P < \overline{P}$ condition a) is not satisfied, violating the intuitive criterion.

We now show that $\left(P^{L^*}, \overline{P}\right)$ is the only separating equilibrium that satisfies the intuitive criterion. If $P^{'} > \overline{P}$, condition a) is not satisfied. Then, $P^{'} \geq \overline{P}$. But if $P^{'} < \overline{P}$, there is no separating equilibrium, since any deviation at $P^{'} < \overline{P}$ is profitable for the low-quality seller. Then it must be $P^{'} = \overline{P}$, and $\left(P^{L^*}, \overline{P}\right)$ is the only separating equilibrium that satisfies the intuitive criterion. □

Corollary 10 *Suppose that* $\bar{D}(P, \mu, 1) \leq \frac{1}{2}$. *Then*

- $D_{\theta P} > 0$ implies $\frac{\partial \mu^Y(P,\mu)}{\partial P} - \frac{\partial \mu^N(P,\mu)}{\partial P} \geq 0$
- $D_{\theta P} < -\lambda \frac{\mu}{1-\mu}$ and $\frac{\partial}{\partial q}\left[P \frac{\bar{D}_P(P,\mu,q)}{\bar{D}(P,\mu,q)}\right] < 0$ imply $\frac{\partial \mu^Y(P,\mu)}{\partial P} - \frac{\partial \mu^N(P,\mu)}{\partial P} \leq -\lambda.$

Proof Consider separation through high prices ($D_{\theta P} > 0$). Condition $\frac{\partial \mu^Y(P,\mu)}{\partial P} \geq \frac{\partial \mu^N(P,\mu)}{\partial P}$, is equivalent to:

$$\frac{\left[\overline{D}_P(P,\mu,1)\overline{D}(P,\mu,0) - \overline{D}_P(P,\mu,0)\overline{D}(P,\mu,1)\right]}{\left[\mu\overline{D}(P,\mu,1) + (1-\mu)\overline{D}(P,\mu,0)\right]^2}$$
$$\geq \frac{\left\{\left[\overline{D}_P(P,\mu,1)\overline{D}(P,\mu,0) - \overline{D}_P(P,\mu,0)\overline{D}(P,\mu,1)\right] + \left[\overline{D}_P(P,\mu,0) - \overline{D}_P(P,\mu,1)\right]\right\}}{\left[\mu\left(1-\overline{D}(P,\mu,1)\right) + (1-\mu)\left(1-\overline{D}(P,\mu,0)\right)\right]^2}$$
$$\left[\overline{D}_P(P,\mu,1)\overline{D}(P,\mu,0) - \overline{D}_P(P,\mu,0)\overline{D}(P,\mu,1)\right]\left[\mu\left(1-\overline{D}(P,\mu,1)\right) + (1-\mu)\left(1-\overline{D}(P,\mu,0)\right)\right]^2$$
$$\geq \left[\overline{D}_P(P,\mu,1)\overline{D}(P,\mu,0) - \overline{D}_P(P,\mu,0)\overline{D}(P,\mu,1)\right]\left[\mu\overline{D}(P,\mu,1) + (1-\mu)\overline{D}(P,\mu,0)\right]^2$$
$$+ \left[\overline{D}_P(P,\mu,0) - \overline{D}_P(P,\mu,1)\right]\left[\mu\overline{D}(P,\mu,1) + (1-\mu)\overline{D}(P,\mu,0)\right]^2$$

Note that $\left[\overline{D}_P(P,\mu,0) - \overline{D}_P(P,\mu,1)\right] < 0$ since $D_{\theta P} > 0$. Therefore a sufficient condition is given by

$$\mu\left(1-\overline{D}(P,\mu,1)\right) + (1-\mu)\left(1-\overline{D}(P,\mu,0)\right) \geq \mu\overline{D}(P,\mu,1) + (1-\mu)\overline{D}(P,\mu,0)$$
$$\mu\bar{D}(P,\mu,1) + (1-\mu)\bar{D}(P,\mu,0) \leq \frac{1}{2}$$
$$\bar{D}(P,\mu,1) \leq \frac{1}{2}.$$

Then consider separation through low prices ($D_{\theta P} < 0$). Condition $\frac{\partial \mu^Y(P,\mu)}{\partial P} - \frac{\partial \mu^N(P,\mu)}{\partial P} \leq -\lambda$, is equivalent to:

$$\lambda + \frac{\mu(1-\mu)\left[\overline{D}_P(P,\mu,1)\overline{D}(P,\mu,0) - \overline{D}_P(P,\mu,0)\overline{D}(P,\mu,1)\right]}{\left[\mu\overline{D}(P,\mu,1) + (1-\mu)\overline{D}(P,\mu,0)\right]^2}$$
$$\leq \frac{\mu(1-\mu)\left\{\left[\overline{D}_P(P,\mu,1)\overline{D}(P,\mu,0) - \overline{D}_P(P,\mu,0)\overline{D}(P,\mu,1)\right] + \left[\overline{D}_P(P,\mu,0) - \overline{D}_P(P,\mu,1)\right]\right\}}{\left[\mu\left(1-\overline{D}(P,\mu,1)\right) + (1-\mu)\left(1-\overline{D}(P,\mu,0)\right)\right]^2}$$

Noting that

$$\frac{\mu(1-\mu)\left[\overline{D}_P(P,\mu,1)\overline{D}(P,\mu,0) - \overline{D}_P(P,\mu,0)\overline{D}(P,\mu,1)\right]}{\left[\mu\overline{D}(P,\mu,1) + (1-\mu)\overline{D}(P,\mu,0)\right]^2}$$
$$\leq \frac{\mu(1-\mu)\left[\overline{D}_P(P,\mu,1)\overline{D}(P,\mu,0) - \overline{D}_P(P,\mu,0)\overline{D}(P,\mu,1)\right]}{\left[\mu\left(1-\overline{D}(P,\mu,1)\right) + (1-\mu)\left(1-\overline{D}(P,\mu,0)\right)\right]^2}$$

holds if $\frac{\partial}{\partial q}[P\frac{\bar{D}_P(P,\mu,q)}{\bar{D}(P,\mu,q)}] < 0$ (demand for good quality products is more elastic than demand for bad quality products), and $\bar{D}(P,\mu,1) \leq \frac{1}{2}$ (demand for good quality is sufficiently low). Then we just need to verify that

$$\lambda \leq \frac{\mu(1-\mu)\left[\overline{D}_P(P,\mu,0) - \overline{D}_P(P,\mu,1)\right]}{\left[\mu\left(1-\overline{D}(P,\mu,1)\right) + (1-\mu)\left(1-\overline{D}(P,\mu,0)\right)\right]^2}$$

which is implied by

$$\lambda \leq \frac{\mu(1-\mu)\left[\overline{D}_P(P,\mu,0) - \overline{D}_P(P,\mu,1)\right] \mid}{\left(1-\overline{D}(P,\mu,0)\right)^2}$$

which in turn is implied by $D_{\theta P} < -\lambda\frac{\mu}{1-\mu}$.

□

Appendix B

Proof of Lemma 2

A necessary condition for C1 to be satisfied is that the low-type monopolist charges in equilibrium the full-information monopoly price P^{L^*}: the maximizer of $\Pi(L,P,\mu=L)$. Moreover C3 requires that the high-type monopolist should not have any incentive to deviate from the equilibrium price, as such deviation implies pessimistic beliefs. Then it is sufficient to control for the best deviation, which occurs at P^{H^*}: the maximizer of $\Pi(H,P,\mu=L)$. Then, two conditions are sufficient for the existence of a separating equilibrium:

1. $\Pi\left(L,P^{L^*},\mu=L\right) \geq \Pi\left(L,P^H,\mu=H\right)$
2. $\Pi\left(H,P^H,\mu=H\right) \geq \Pi\left(H,P^{H^*},\mu=L\right)$ □

Proof of Proposition 4

We first analyze SCP1:

$$\begin{aligned}\frac{\partial^2\Pi(\theta,P,\mu)}{\partial\theta\partial P} =& D_{\theta P}(\theta,P,\mu)\left[\lambda P+\pi\left(\mu^Y(P,\mu)\right)-\pi\left(\mu^N(P,\mu)\right)\right]\\ &+D_\theta(\theta,P,\mu)\left[\lambda+\left(\frac{\partial\pi\left(\mu^Y(P,\mu)\right)}{\mu^Y(P,\mu)}\frac{\partial\mu^Y(P,\mu)}{\partial P}\right.\right.\\ &\left.\left.-\frac{\partial\pi\left(\mu^N(P,\mu)\right)}{\mu^N(P,\mu)}\frac{\partial\mu^N(P,\mu)}{\partial P}\right)\right]\end{aligned}$$

Since demand is increasing in quality $D_\theta(\theta,P,\mu)=\overline{D}(P,\mu,1)-\overline{D}(P,\mu,0)>0$, profits are increasing and convex in beliefs, then conditions 1 and 2 imply the result. Consider now SCP2:

$$\begin{aligned}\frac{\partial^2\Pi(\theta,P,\mu)}{\partial\theta\partial\mu} =& D_{\theta\mu}(\theta,P,\mu)\left[\lambda P+\pi\left(\mu^Y(P,\mu)\right)-\pi\left(\mu^N(P,\mu)\right)\right]\\ &+D_\theta(\theta,\mu,P)\left(\frac{\partial\pi\left(\mu^Y(P,\mu)\right)}{\mu^Y(P,\mu)}\frac{\partial\mu^Y(P,\mu)}{\partial\mu}\right.\\ &\left.-\frac{\partial\pi\left(\mu^N(P,\mu)\right)}{\mu^N(P,\mu)}\frac{\partial\mu^N(P,\mu)}{\partial\mu}\right)\end{aligned}$$

Since $D_\theta(\theta,\mu,P)>0$, and profits are convex in beliefs, then condition 3 is a sufficient condition for SCP2 to be satisfied. □

Proof of Proposition 5

Analogous to Proof of Proposition 4. □

Proof of Corollary 6 Condition 3 in Proposition 4 is equivalent to

$$\frac{\mu^2}{(1-\mu)^2}\leq\frac{\overline{D}(P,0)}{\overline{D}(P,1)}\frac{\left[1-\overline{D}(P,0)\right]}{\left[1-\overline{D}(P,1)\right]}$$

which is implied by $\left(\frac{H}{1-H}\right)^2\leq\frac{\bar{D}(v,0)}{\gamma\left[1-\gamma\left(1-\bar{D}(v,0)\right)\right]}$, where v is the maximum willingness to pay of ineslastic consumers. □

Proof of Corollary 7

Given $\frac{\partial \mu^Y}{\partial P} = 0$, condition 2 in Proposition 5 is equivalent to

$$(\alpha - 1)\frac{1-\mu}{\mu}\frac{\mu^{N^2}|\bar{D}_P(P,0)|}{(1-\alpha\bar{D}(P,0))^2} \geq \lambda$$

which is implied by the parametric condition

$$\mu^{N^2}\frac{1-H}{H}(\alpha - 1)|\bar{D}_P(P,0)| \geq \lambda$$

On the other hand, it is easy to see that the condition 3 in Proposition 5 is implied by

$$\left[\frac{H}{1-H}\right]^2 \leq \alpha$$

□

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